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# AIR CUSHION VEHICLE CONTROL SIMULATION

Proposed Amphibious Assault Landing Craft
Program Plan

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Final Report

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AALC PROGRAM

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# CONTROL SIMULATION

## ABSTRACT

This report is a summary of simulation needs and recommendations
specific to the current Navy Amphibious Assault Landing Craft (AALC)
Program which is developing high speed amphibious Air Cushion Vehicles
(ACV). The recommendations fall within three categories: mathematical
modelling, hybrid computer facility, and man-in-the-loop simulation. To
a large extent the needs and recommendations presented here are applic-
able to other Navy programs as well, since many factors are common to
any craft development program: the nature of dynamical system model-
ling, of mathematical seaway generation, of parametric craft or ship
design, of stability and control analysis, of subsystem implementation
and integration, of craft testing and manning. In particular, the recom-
mendations on mathematical modelling should be immediately applicable
to the Navy Artic ACV Program. The recommendations of the Hybrid
Computer Facility are applicable to any multi-degree-of-freedom craft
or ordinance development, especially if a real-time control system or
autopilot must be designed (hydrofoil crafts, PT boats, submarines,
torpedos, missiles). Finally, the recommendations for man-in-the-loop
simulation are specific to any craft development program where visual
perception by a watch officer or a helmsman is an important element in
controlling craft motion and maneuvering.

by Pierre Dogan
August 1971

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# CHAPTER 1

## HISTORICAL PERSPECTIVE,
## CONCLUSIONS AND RECOMMENDATIONS

### 1.1   Introduction

Sophisticated simulations of manned vehicles motions through an environ-
ment have been performed numerous times in the recent past: the Apollo
Command and Lunar Modules Simulation[1]; the Deep Submergence Rescue
Vehicle (DSRV) Simulation[2]; the Jetliner Simulation for Obstacle Avoid-
ance and Air Traffic Control[3]; Army Helicopter TAC Simulation[4];
Hydrofoil Boats Simulation[5]; etc.   Such large simulations by necessity
operate in real-time since their purpose is to evaluate craft controllability
with man-in-the-loop and to research or design advanced subsystems in-
volving prototype versions of actual flight hardware or software.  Such
simulations have been, or still are, invaluable research and development
tools that have promptly paid back their investments.  While a lack of
scope or useful planning may lead to non cost-effective simulations, it is
clear that the experience and lessons gained from the cost-effective simu-
lation efforts, enumerated above, illuminate the needs and spell out the
potential gains to be expected from simulation by the Navy in its current
ACV programs as well as in other craft and vehicle development programs.

The designs of multi-degree-of-freedom dynamic systems with man-in-
the-loop and with strong interactions between the component subsystems
require an accurate portrayal of such interactions.  A realistic portrayal
is necessary in order to assess the full impact of design decisions on a
spectrum of craft characteristics such as:  static and dynamic stability,
maneuverability, operability, habitability, casualty survivability, etc.
Clearly, many ACV design decisions are made without the tool of a simu-
lator; however, a design process usually proceeds on an iterative, guess -

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1.   MIT Draper Laboratory, NASA Contract
2.   MIT Draper Laboratory, Navy Contract
3.   MIT Flight Transportation Laboratory, U.S.A.F. Contract
4.   MIT Draper Laboratory, Army Contract
5.   Boeing Company, Navy Contract

try - verify method. Where large investments and long lead times are involved, it is important to immediately assess the full impact of design decisions before full scale craft trials. A real-time man-in-the-loop simulator is an excellent way to alleviate the high risk situations of having to wait for full scale craft trials in order to fully assess the implications of early design decisions.

It is worthwhile to summarize here two appropriate examples of heavy simulator use by other Navy programs: the Hydrofoil and the DSRV simulations. It should not be difficult for the reader to translate applicable events, gains and experiences to the AALC development program.

## 1.2    Short History of Navy Hydrofoil Simulation (PCH, AGCH)

Modern high speed hydrofoil crafts probably presented the first example of Navy crafts where automatic motion control cannot be conceived as an optional, add-on feature, but rather as a necessary ingredient from the onset to ensure a safe and efficient craft operation. The hydrofoil craft motion simulation sponsored by the Navy over several years presents a remarkable example of a successful, timely, and in retrospect, mandatory, real-time simulation effort. From conceptual design through full scale trials, the simulation supported the craft development. Stability and parametric studies were conducted; control surfaces and actuators were sized; craft control systems were designed; safe operational envelopes were defined; reliable references and performance predictions were generated by the simulator for the craft trials; and finally a repeatable and reliable craft model could be correlated with full scale data. This permitted conducting rapid investigations of field problems, redesigns of marginal systems as well as the check-out of altered systems before incorporation into the trial craft. The ultimate cost-effectiveness and usefulness of the Hydrofoil Simulation effort is not only measured by its role in system design but also by the number of outright catastrophic events that were prevented during the sea trials, and by the efficiency that it permitted in designing, planning and monitoring daily test activities and in analyzing and correlating the trial data. It is not conceivable that such tasks could have been reasonably conducted without a real-time simulator or with the sole support of the full scale craft and its logistics. Furthermore, at program completion an exhaustive, documented and well exercised simulation constitutes a repository of knowledge and engineering data that permits the Navy to capitalize on the newly gained experience.

Advanced hydrofoil designs can be conducted based on the extrapolation of previous baselines as predicted by the simulation. The latter becomes a structured data bank as well as a means for conducting iterative designs. Finally, the real-time simulation experience gains may be applied to the development of a crew trainer to be used as a Naval Training Device.

Despite problems caused by nonlinear lift and drag, by venting and cavitation, by hull impact, etc., the essentially high speed craft motion permitted a reasonable linearization of the problem which in turn rendered an analog computer solution adequate. Substantial effort was invested in the derivation of equations of motion, in strut and foil modelling, and in the generation of "realistic" mathematical seaways. Analog computer mechanizations were effected, capitalizing on previous aerospace experience with such computing devices. Correlation with full scale trials was achieved successfully for most cases. Immediate dividends were derived from the ability to design and check out on-line control system configurations in actual hardware, a task easy to perform with the help of a patchable analog computer. In fact, it happened that the very philosophy of the automatic controls was modified thanks to simulation experience. For instance, the turning of the hydrofoil craft is obtained by banking, a clear requirement for coupled roll-yaw control and indirect azimuth control. The problem of coordination in the turn, of lateral stability and of roll-sway-yaw coupling was properly rendered on the simulator. Similarly the height- or depth-keeping control problem, with the effect of orbital velocities of an agitated seaway, lent itself ideally to analysis and design by means of a real-time simulation. Gain adjustments, dynamic tuning and prototype check-out were effected through the simulator.

An important component of the simulation of the hydrofoil craft was an efficient data acquisition system. The collection of data on board the trial craft was performed in analog and digital form; the raw data was processed through a data acquisition system and eventually fed in compatible format into the simulation. It is expected that the experience gained in the data acquisition area by the hydrofoil program would be directly applicable to other Navy programs and, in particular, to the full scale trial of the AALC program ACV's.

## 1.3    Short History of the DSRV Simulation

Characteristic of the Deep Submergence Rescue Vehicle (DSRV) mission is a requirement for accurate and simultaneous six-degrees-of-freedom

control to permit the d○ ̄king of a 50-foot long submersible to a fixed, but uncooperative distressed submarine lying on the ocean floor, or to a co-operative but moving mother ship, either a catamaran surface ship or a specially fitted attack submarine. For effecting successful docking, the following maneuvering cons ̄aints must be met simultaneously: pitch and roll alignment between the DSRV and the target hatches, a reasonable azi ̄uth alignment between the DSRV main thruster and a local current of st ̄ ̄th up ○ or · and a half knot, a horizontal hatch positioning within an e○ ̄e of ̄wo in○h○s, and finally a r○asonable "softlanding" velocity to avoi ̄ ̄sh ̄amap ̄ ○○○eral conceptual design iterations lead to a shrouded main ○ropeller, ○○○e○ ateral thrusters and mercury pumps as principal actuato s. The ○○○rements for manual and automatic stability augmentation ha ̄ to be issued early, and, in particular, the question of feasibility and efficiency in attitude and position contro ̄ by a pilot had to be answered reasonab ̄○ arly to enable a timely design of the controls and displays.

Several DSRV sir ̄ulation ○fforts were started at various locations (Table 1-1). The following 12 points, roughly in chronological order and spread over a 3 year period, summarize the development and use of the hybrid, digital-analog simulation of the DSRV. The reader should bear in mind that it would have been impossible to attain these results without heavy use of a simulator.

1. The obtainment of equations of motion. Formulation of format, analytical derivations, specification of coefficients and supporting model testing at NSRDC and a private facility. Contribution by the prime vehicle contractors. Consolidation of all modelling inputs.

2. The implementation of a real-time, six-degrees-of-freedom simulator to support the Ship Control studies including TV and sonar simulation. Adoption of a hybrid digital-analog facility.

3. The design of a Hover and Cruise Control System for DSRV. This entailed many iterative designs with man-in-the-loop studies and the simulation of control transfer functions.

4. The actual detailed design of an Analog Autopilot and a Digital Autopilot, first in breadboard versions, later in prototypes. Simulation permitted optimizing the designs early, and testing system subassemblies and transfer functions, including scaling and saturation effects.

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Table 1-1  History of DSRV Computer Simulation

| | YEAR | COMPANY | PURPOSE | SCOPE AND LANGUAGE | COMMENT BY MIT ON USEFULNESS OR SHORTCOMINGS |
|---|---|---|---|---|---|
| 1 | 1965 | NAFI Naval Avionics Facility at Indianapolis | Simulation for preliminary Control Systems design | All Analog Simulation; 6 DOF, but vastly simplified equations | •Funding by Federal Government. •Discontinued early. •Of limited use. •Work entirely redone by Ship Control Contractor. |
| 2 | 1966 | SPERRY | •Man-in-loop investigation •Studies of anchors, winches •Intended design of control system | Real-time hybrid | •Funding by LMSC, (subcontract). •Discontinued early. •Outdated equations of NR-1, not applicable to DSRV. •Very slow and small computer. Digital-analog facility not adequately sized for full problem. •No feedback into Control and Display system design. Inconclusive study. |
| 3 | 1966 | Cornell Aeronautical Lab | Control system design | •Real-time •Analog only •Man-in-loop | •No impact on ship control design •Results obtained indicate need for more studies  Limited use because analog only. Contract discontinued early |
| 4 | 1967-1968 | MIT #1 | Preliminary design of Ship Control | •6 DOF vehicle equations •Control system equations •FORTRAN | Useful for preliminary design However, extremely slow and wasteful of computer time Was later superseded by hybrid system |
| 5 | 1968-1969 | MIT #2 | •Ship Control design checkout •Closed loop performance prediction | •Non real-time •6 DOF vehicle equations •Control system equations •MAC language | •Detailed plot of every variable involved in the system •Convenient outputs, but quite expensive •Poor turn-around time. Provides less information than hybrid simulation  Useless as a design tool •Probably should have been discontinued earlier •Impossible to evaluate man-in-loop |
| 6 | 1967-1970 | MIT #3 | •6 DOF vehicle simulation •Simulation of control system •Man-in-loop •Checkout of control system •Checkout of software •Checkout of hardware •Crew training | •Real-time •Hybrid (Digital/Analog) •Machine language | Highly successful and cost effective simulation  All objectives were met  Should have been relied upon early as sole computer support  Simulation presently supporting sea trials  Soon to be expanded to include simulation of and docking to mother submarine |
| 7 | 1968-1969 | LMSC | Open-loop vehicle performance prediction | Non real-time | •Useful for LMSC to predict their own performance as a prime contractor •Duplicated results of MIT #1,#2,#3 •Will be duplicated partially by Northrop |
| 8 | 1967-1969 | NORTHROP | •System analysis •Performance prediction for helping DSSPO in specifying acceptance criteria | •Non real-time •6 DOF vehicle equations •Control system equations | Same as MIT #2 which it duplicates same shortcomings |
| 9 | 1969-1970 | University of New Hampshire | Investigate Ship Control concepts | •Non real-time •All digital | •Contract sponsored by NASA, encouraging University Research in control systems •Substantial work invested in merely programming vehicle 6 DOF motion •Repeats problems and mistakes of MIT #2, Northrop, etc  Poor means of investigating control system concepts |

5. The programming of the Digital Autopilot proceeded, supported by the simulation, the breadboard and later the prototype hardware. Static and transient testing permitted on-line software design, debugging and integration.

6. Man-in-the-loop studies continued, TV and Sonar displays were fully and realistically mocked up, interactive and quickened displays were studied and implemented using the simulator.

7. Simulation was increased to encompass all Navigation sensors, including an Inertial Navigator, a Doppler Sonar, Acoustic Transponders, etc. This permitted the software design and integration of the DSRV Navigation System.

8. All systems in the prototype configuration were simultaneously run with the simulator providing a real-time environmental background. Ship Control was integrated with Navigation and other functions. Man-in-the-loop studies continued, DSRV mission software was used as a valuable design tool in debugging hardware and software.

9. Simulation was used to plan and define safe and efficient sea trial profiles. A data acquisition system was designed from concept to hardware and was integrated using the simulator.

10. Crew training was performed using the simulator. The DSRV-1, DSRV-2 and Test Pilots crews were trained, totalling some 350 hours of simulation "stick time".

11. DSRV sea trials support. Field situations are reported daily and specific discrepancies are investigated on the simulator. Rapid fixes are generated while some longer term solutions are initiated by redesign. A major problem with the propulsion system was investigated by a real-time modelling of motor speed controllers on the simulator. Recommendations for redesign were made.

12. Reduction and analysis of full scale DSRV sea trials data is proceeding with heavy support from the simulator. Model updating and some subsystem redesign or "tuning" will follow. Model updating requires the solution to the "inverse problem", i.e., the extraction of coefficients for the equations of motion from full sea trial data.

The DSRV simulation facility is slated to become a Navy Training Device by the end of fiscal year 1972 thus completing a remarkable "cradle to grave" cycle of supporting the acquisition of a system from concept to operational hardware.

### 1.4 Modelling Sophistication and Hybrid Approach

There are several lessons to be retained from the DSRV simulation experience − two of which will be immediately discussed here. First, the axiom that a simulator is no better than the mathematical models upon which it is based may have a special connotation. The DSRV prime contractor was concerned with powering and propulsion problems. The amount of hydrodynamic data required for such "first order" engineering designs is rather narrow: overall drag in each translational degree of freedom; enough data to size the propeller, the motor-speed controllers and the batteries. The DSRV "sensors and controls contractor", on the other hand, required accurate and sophisticated modelling of hydrodynamics with first and higher order terms, cross-axis couplings, for "free-stream" operations as well as "proximity" hydrodynamics when the DSRV hovers in the vicinity of a distressed submarine in an ocean current, or when it rendezvous with a moving submarine. The discrepancy in modelling sophistication between the needs of the "vehicle prime contractor" and the "sensors and controls contractor" was resolved by the latter initiating all the modelling requirements and the former supplying them through coordinated functional interfaces (contractually, tne responsibility for hydrodynamic data remained with the prime contractor). In the case of the AALC contractors, each one is simultaneously "vehicle" and "sensors and controls" contractor. Superficially, there seems to be no conflict in such an arrangement, but MIT feels that in fact it may be the cause for a lack of incentive in developing sufficiently sophisticated mathematical models.

Second, in contrast to the hydrofoil craft case, only a hybrid digital-analog computer could perform the DSRV simulation reasonably well because of a variety of reasons: dynamic range of frequencies and amplitudes, bandwidth requirements, numerous nonlinearities, flexible "hands on" monitoring and recording, problem "hold" capability and on-line system tuning or patching; easy real-time interfacing capabili.), .,nergism in complex, nonlinear, multi-mode simulation. If the hydrofoil simulation capitalized on previous analog computer experience, the DSRV simulation cost-

effectiveness is mainly the result of a direct borrowing of hybrid techniques from the Apollo simulation conducted in the 60's at MIT. This "hybrid" trend has been confirmed in recent years (see: NASA Nerva Project) and offers, with new 4th generation digital computers and modern analog devices, the most flexible, expandable, controllable and cost-effective means of simulating complicated systems in real-time.

## 1.5 Conclusions and Recommendations on a Naval Simulation Facility Applicable to the AALC Program and Other Navy Programs

Large simulation efforts are usually idiosyncratic: their development and structure is heavily conditioned by the problem at hand. The specific mission requirements of the AALC program would, of course, require a highly directed simulation. However, the high cost inherent in a craft motion simulation facility is believed to be of such magnitude that a single Navy program, except under unusual circumstances, would be unable to presently afford the initial capital investment singlehandedly. And yet this study points out that the sophistication level required for useful ACV studies demands a computer facility of adequate size. It also suggests that modern man-in-the-loop visual and kinesthetic equipment be used. It is hoped that the dilemma will be resolved by consolidating the simulation needs of several Navy programs in order to achieve the necessary capital investment. Large simulations of multi-degree-of-freedom vehicles moving through an environment have in common certain desirable features such as realism, flexibility, cost-effectiveness, growth potential, etc. The following conc. ns reached by MIT do not itemize and explain these evident requirements, but tend to point out the less obvious aspects of large simulation efforts in general, and in particular give specific recommendations to the AALC program that should be followed to obtain a useful ACV simulation.

### 1. Conclusion : Present ACV Simulation Status

MIT has found the present (up to June 1971) level of ACV simulation rather rudimentary. Both the Bell Aerospace and the Aerojet Corporations, the two AALC contractors, have resorted to simulations in various forms but not in the needed depth as is suggested by this MIT report [3] [4].

The Bell hybrid simulation was short-lived and had reliability problems.
It is believed that its size was small and that the throughput was limited.
Bell's latest plan seems to be an all digital simulation effort to be
launched at their new plant site in Louisiana. The Bell ACV visual
simulator, an adaptation from a moon landing simulation, was found
insufficient for the in-depth simulation recommended by MIT. The
prime results of the Bell man-in-the-loop ACV simulator appears to
show the intricacies of manual controls, the potential problem raised
by the too numerous control options available and in suggesting a more
concerted effort in the ACV control area. The Bell visual simulator
is an interesting experience and a clever use of existing equipment, but
its usefulness is very limited. The analog computer driving it has
the inherent limitations of all analog facilities: the electro-optical
simulation offers no motion within the scene, a limited panoramic
view, no heave and pitch motion, no seaway, no surf, no correlation
between dynamic inputs of waves and visual simulation, and most
important, no potential to improve on any of these shortcomings.

At this time it is believed that the Aerojet General Corporation may be
embarking on a hybrid digital-analog (Sigma 5) simulation. In MIT's
opinion this effort will be low-keyed because of the relatively high
costs involved. Furthermore, any large scale simulation effort is
predicated on the obtainment of sophisticated mathematical models,
which do not exist and are not a present goal for any of the two
contractors.

In conclusion, none of the two AALC contracts has identified a strong
need for simulation nor is planning a simulation effort of the scope
defined herein, and it is believed that only minimal, all digital simu-
lations would be performed by either contractor in the near future
precluding in-depth man-in-the-loop studies.

The present simulation of the Artic ACV program was found to be in
its elementary stage, apparently modelling an ACV as a point mass.
Attempts are being made to upgrade this simulation and there is no
doubt that a commonality of interest exists between the AALC and the
Artic ACV program.

2. Recommendation : <u>Desirable Scope of ACV Simulation for the</u>
<u>AALC Program</u>

A powerful, real-time ACV simulation effort is recommended by MIT
in view of the importance to the Navy of developing high speed ACV's.
The simulation support would parallel the histories of Hydrofoil and
DSRV simulations, and help maintain cost-effectiveness in developing
the craft with its subsystems including its control and displays and in
evaluating ACV's crews. The Navy's desire to have a craft operable
by low skilled personnel demands a simulator approach for control
design. The simulator must be composed of sophisticated mathe-
matical models, capable of trend predictions, an adequate real-time
computer facility, and, unlike the hydrofoil case or even the DSRV
case, an adequate complement of modern equipment to render the
man-in-the-loop requirements, i.e., visual and kinesthetic perception.
The MIT suggestion for visual simulation and the inherent modelling
difficulties in deriving ACV equations of motion, render the recom-
mended simulation challenging and desirable.

3. Conclusion : <u>Danger of Downgrading or Precluding ACV Simulation</u>

The productivity and usefulness of a simulation is directly dependent
upon the incentives which motivate the people running the simulator
and/or the corporation contractually tasked. The hydrofoil and DSRV
experiences indicated that a simulation can be cost-effective if it is
tied down to an important and specific design goal (such as the de-
velopment of a craft control system). Under such conditions, the
usefulness of a simulator, with little additional investment, <u>invariably</u>
<u>transcends its original specific purpose and by synergy gets to be</u>
<u>used for broader tasks</u> (such as indicated in Figure 2-1 of Chapter 2).
In the hydrofoil program, it was recognized early that the craft con-
trol problem demanded specific attention and dictated a real-time
simulation approach. In the DSRV case, the procurement of the sen-
sors and controls proceeded through a special contractor who thus
had the incentive to allocate the resources for a productive and cost-
effective simulator. In the ACV case, the AALC program office
recognized the importance of the craft control problem and addressed
the issue by mandating this study. It appears that neither of the
present two contractors for an experimental AALC craft would embark
on a sizable and sophisticated simulation effort within the scope of

their present contracts. This is important to recognize since it is clear by now that the use of a cost-effective simulator would cover much broader grounds than the design of a craft control system. The latter is usually only the nucleus activity that initially justifies setting up a simulation. Herein lies the danger for the current AALC program — When major technological developments must proceed on a broad front (in skirt, lift, powering, propulsion and structure designs) one may be tempted to downgrade the control problem. This in turn may downgrade the importance of planning a simulator in the craft development because of the erroneous belief that a simulator is exclusively subordinated to the task of a craft control design. Reliance on the human adaptability of the test pilots who will crew the trial craft, and the belief that "black box" type additions may later provide stability and dynamic augmentation if needed, may further reinforce this tendency. The postponing or outright preclusion of real-time, man-in-the-loop simulation activities in the AALC program would then not only prevent the remarkable synergism and risk alleviation that were obtained in the Hydrofoil and DSRV programs, but also leave hidden aspects of developmental risk covert for longer periods of time. Meanwhile, if no explicit simulation effort is started, the codification and compilation of engineering data related to ACV designs — a stated program objective before transition to NAVSEC — would be missing an important agent for coalescing and structuring design experience as well as missing a unique predictive tool.

4.   Conclusion : Need for Concentration of ACV Simulation Efforts

The scattering of limited Navy resources among disjointed, low return simulation efforts must be avoided in any craft development program. Scarce resources must be allocated to obtaining a minimum "critical size" of simulation equipment below which the unavoidable simplifications in mathematical modelling would compromise realism and preclude useful returns. (Table 1-1 gives an interesting example of how easily simulation efforts can be misled. Each of the nine efforts was intended to simulate motions in six degrees of freedom, most of them with some type of control system. Review of evidence indicates that at least seven of the nine simulations were of little or no use, due to deficient models, ill-defined objectives, inadequate mechanization, or useless duplications.) The concentration of simulation efforts should not only occur within a single Navy program, but con-

solidation should also occur between several Navy programs. It is believed that the sharing of capital investment and overhead costs will permit setting up a Naval Simulation Facility. The "critical" size of common equipment of such a facility is estimated at roughly $ 1,000,000 in computer equipment and about $ 700,000 for visual-kinesthetic simulation equipment.

5. Conclusion : Present Status of ACV Equations of Motion

Both AALC contractors have done a great deal of modelling work on thrusters and effectors, on skirt drag, momentum drag from turning air flow, aerodynamic drag, etc. Overall, this data is quite good, although some additional data is felt to be necessary in certain areas (more thorough testing of cushion pressure conditions as a function of fan speed and gap size; large yaw angle data; high Reynolds number data). The major weakness of the present ACV model lies in the cursory treatment of the free surface effects, based only on some steady-state, towing-tank-obtained lumped data.

The present models are unreliable in predicting maneuvering, transient motion in surge and yaw, "instantaneous drag" as well as instantaneous, time-domain (non-averaged) behavior in waves and surf.

The available seaway models are adequate, albeit care must be exercised in optimizing their formats for computer use. The available surf models seen by MIT [5] appear cumbersome and overly complicated for the intended simulation objective.

6. Conclusion : Difficulties in Free Surface Modelling

A major conceptual difficulty hampers efforts in improving ACV models : the history dependence of ACV forces and moments, or equivalently, the frequency dependence of coefficients when equations are assumed to be second order with "constant" coefficients. Recent work surveyed in the literature and discussions within the MIT Ocean Engineering Department corroborate the fact the the history dependence, or co-efficient-frequency-dependence may preclude a high degree of simulation realism for ACV maneuvering if only traditional and cursory treatment is given to the problem. Although the mathematical treatment of traveling pressure disturbances on a water free surface is

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infinitely more tractable than the mathematical description of maneuvering displacement ships, the fact remains that a sizable, but not unreasonable, amount of concentrated analytical effort remains to be done.

7. <u>Recommendation</u> : <u>Upgrading of ACV Mathematical Models</u>

Chapter 3 spells out a step by step plan for upgrading ACV equations of motion. The first step is to collate and structure the available data. Beyond that, the important free surface effects should be handled in two ways:

   A. A low risk, moderate return, "amnesic" model, based on standard scale model test techniques, and analytical correlations. The dominant features would be perturbational modelling about equilibrium points that can have large yaw angles, and a "sliding" equilibrium point in the computer mode. The analytical manpower cost is estimated at 10 manyears plus the cost of equipments.

   B. A higher risk, long term, higher return, "non-amnesic" model based on analytical definitions of the water surface underneath the air cushion and properly correlated with experimental data. It is believed that this powerful model is attainable within 2 years at the cost of an approximate 10 manyears of analytical effort and associated model testing cost.

Approach A enables a fast, but still useful simulator development until the mathematical model of approach B can be adopted by the then-proven simulation facility.

8. <u>Recommendation</u> : <u>Modelling Efforts must be Concentrated</u>

The same agency or group of people should be tasked by the Navy to conduct, or at least partially conduct but <u>totally</u> supervise, the <u>analysis</u>, the <u>experiments</u> and the <u>computer programming</u> involved in the proposed plans. Since the computer programming can be done in FORTRAN (see below) and since the intertwining of analysis and towing tank or wind tunnel experimentation is intimate, this recommendation is not only quite reasonable for attaining cost-effectiveness, but essential to guarantee any success.

9.  Recommendation : <u>Visual Simulation from an ACV Cockpit is Needed</u>
    <u>and can be Obtained at a Reasonable Price</u>

Visual simulation needs are discussed in Chapter 4. The most unex-
pected finding that occurred during the MIT study on ACV simulation
needs is the dramatic breakthrough that seems to have occurred re-
cently in the state-of-the-art of computer scene generation. A study
by the Naval Training Device Center as recent as 1970[6] still did not
recommend the use of computer generated scenes. It appears now,
however, to be feasible at reasonable cost to implement a "window"
scene with dynamics of the point of perspective as well as motion
within the scene, using standard projection equipment and scene gen-
erating electronic hardware driven by a "host computer". The scene
can have a wide panoramic angle, a high resolution, good contrast
and can be in focus for all ranges, while objects in the scene have
smoothed edges and shaded areas. The "host computer" can be the
problem computer of the Naval Simulation Facility, while the cost of
the scene generating electronics is only around $ 350,000, a tremen-
dous decrease from anything available until recently. All problems
and shortcomings of electro-optical systems are thus by-passed. It
is expected that ocean waves and surf will be rendered and that real-
istic correlation between dynamic force inputs and visual stimulation
to the pilot will be provided. Furthermore, docking to a moving
target or maneuvering alongside another ship or formation flying will
be rendered. Since this is a new emerging technology, a study on
the subject matter is still required before a final design can be com-
mitted. (This is suggested in Figure 2-2, in Chapter 4, and in
Appendix A.)

10.  Recommendation : <u>A Kinesthetic Simulator Should be Considered</u>

It is reommended to provide only heave motion in a kinesthetic simu-
lator. (This does not mean that pitch, roll and yawing motion is not
simulated – all attitude motion and spatial translation should be com-
puted, and the visual scene presentation will reflect these.) It is
believed that the nominal pitch and roll angles achieved by an ACV
of the size of the C 150 do not warrant moving the platform carrying
the ACV cockpit and the simulated crew in these degrees of freedom.
Cockpit heave motion is, of course, a result of both heave and pitch
motion of and about the ACV center of gravity. The potentially large

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acceleration levels (3 g's) to be encountered constitute the major reason for proposing a kinesthetic simulator. It appears that many habitability questions remain unanswered for ACV's operating in a seaway, and that a one-degree-of-freedom kinesthetic simulator will be a useful asset to the Navy in developing high performance crafts.

11.  Recommendation : The Naval Simulation Facility Computer
                      must have a Multi-Access Capability

The most important requirement to account for early is a multi-access computer capability since the Naval Simulation Facility will be shared by several Navy programs. A powerful time-sharing structure should be the objective. This implies that initial systems selection should not preclude the possibility to eventually attain that objective by orderly growth.

12.  Recommendation : Hybrid Computation

The computer system for a Naval Simulation Facility should be a powerful, real-time, hybrid digital-analog system.

13.  Recommendation :

Use modern, multi-console, hybridized analog computers.

14.  Recommendation : Scope and Size of Digital Computer

The digital portion of the hybrid system should be a fast, medium scale computer such as the SEL 8600, the XDS Sigma 8 or the DECPDP 10 (I).

15.  Recommendation : FORTRAN Use is a Must

The operating systems must allow simultaneous operation of real-time programs written in machine language and FORTRAN. A FORTRAN programming capability is important because of the universality and ease of the language.

16. Recommendation :

    Consider the computer vendors in the light of the criteria and
    recommendations of Section 5.6.4.

17. Recommendation :

    MIT recommends that the AALC program and other Navy programs
    come to an agreement soon and follow the step by step plan for
    acquiring and starting a cost-effective, multi-user, real-time
    Naval Simulation Facility as given in Section 5.7.

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CHAPTER 1

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# CHAPTER 2

## NAVY NEEDS FOR SIMULATION

### 2.1    Summary and Conclusion of Chapter

This chapter summarizes various simulation needs that the AALC program
or other Navy programs presently have or will have.  First, a general
framework of Navy objectives is presented for the AALC program.  It is
assumed that the objectives of other Navy programs can be similar.  Then,
the use of simulation is set within the framework of a given Navy vehicle
development program.  Simulation is propounded as an important tool for
the development and acquisition of any new Navy vehicle.  It is concluded
that explicit computer simulation of ACV's can be extremely useful, even
at the present stage of almost completed design by the AALC contractors.
It is suggested that sharing of capital investments and overhead cost be-
tween different Navy programs in need of simulation makes the acquisition
of a simulation facility either feasible or more attractive.  The sophisti-
cation level and specificity of the models defining a craft motion simu-
lator are then discussed.  From there the components of a Naval Simu-
lation Facility are itemized, elaborated upon in the next three chapters.

### 2.2    Navy Objectives in the AALC Development Program

A brief look at Navy objectives is in order if one wants to assess the
desirability of a Naval Simulation Facility.  In discussions with the AALC
program officers and through visits at the two selected AALC contractors,
the Bell Aerospace and Aerojet General Corporations, a definition of
immediate and long terms objectives was given to MIT.  At the heart of
the problem of defining reasonable and unambiguous objectives is the
question of how much design data is needed from the vendors by the Navy.
The objective of obtaining "successful" crafts four (4) years hence may
not quite coincide with the goal of establishing within the Navy a prelim-
inary design capability, i.e., the creation within the Navy of a solid pre-

liminary design capability based on the collection, structuring and extrapolation of design data from the C 150 development experience. Since the ACV under consideration is a developmental version, it is expected that the final craft design to go into production would result from extrapolations and amendments to the present baselines, an effort for which it is claimed that a craft motion simulator is also useful. For the purpose of clarifying alternatives, here are three approaches summarizing program objectives in ascending order of aggressiveness on the part of the Navy.

## Possible AALC Program Objectives

Objective I : The objective of the C 150 development program is to lay the groundwork for production crafts quite similar to either the Bell craft or the Aerojet craft with only small changes to either.

Comment : The data required for preliminary design in this case can probably be obtained within the scope of the present AALC contracts. More specifically, it will be possible to obtain from these test crafts trend curves for the effect of changes in cushion flow, bag pressure, craft weight, shifts in lateral, longitudinal and vertical positions of the C.G., changes in amount of inertia, distribution of installed power, and numerous other variables. The fact that the vendors are required to turn over all their test data will help make this objective realizable. A careful review of Navy requirements for preliminary design data should be made to insure (1) that all reasonable degrees of freedom in the configuration of the test craft are left open, (2) that the required tests are planned and executed by either the Navy or the vendor following delivery of the craft, (3) and that an adequate analytical foundation is developed beforehand to correlate the tests.

Objective II : The objective is to develop the state-of-the-art in ACV of the general size and capability of the C 150 in order for them to be used in either this or some other mission and to allow a gamut of mission objectives to be explored. This will lead to obtaining a handbook on ACV design for vehicles around 150 tons.

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Comment     : More preliminary design data is clearly needed than
              can readily be obtained under the present AALC
              contracts. The following analytical studies should be
              made and correlated with data from the C 150.

       1. Analytical and experimental prediction of
          wave drag, seal drag, and motion as a function
          of craft dimension, loading, velocity, beam-to-
          length ratio, cushion flow, fan characteristics,
          bag design, and seal design.

       2. Structure configurations, stress levels, and re-
          sulting weight as functions of craft size and loads,
          sea state, bag height and shape, construction
          techniques, and desired operating life.

       3. Analysis and prediction of weight, cost and
          reliability of lift and propulsion systems and how
          these relate to the propulsion configuration,
          maneuvering requirements, number of engines,
          gear reduction required, component layout, and
          control elements.

Objective III : A third and still broader objective could be to develop
              ACV technology for a range of vehicle sizes from
              10 tons to 300 tons.

Comment     : It appears that from the test crafts that are under
              development this objective is realistic. The result
              could be a very comprehensive handbook of applied
              ACV technology. Unfortunately, such a handbook
              would be extremely expensive to develop because of
              the wide ranges of craft sizes, propulsion configura-
              tions, and construction techniques that it would have
              to cover  It is certainly out of the scope of the C 150
              development program, but in the long run it may be
              the most efficient approach to opening up ACV tech-
              nology so that unhampered preliminary design and
              mission studies can be done by the Navy.

## 2.3    Desirability of an ACV Simulation

In the framework of the evolving and maturing ACV technology and in view of either the first or second objective stated above, the questions are:

> How useful and how necessary is simulation for Air Cushion Vehicles?

> How is the answer to the first questions modified by the broader context of other Naval Programs, and their simulation needs?

The MIT answer to the first question can be immediately preempted as "very useful to minimize risk and enhance cost-effectiveness" and even "necessary when an explicit objective is the structuring of design and test data for attaining a Navy preliminary design capability". The answer to the second question is that the resources and needs of other Navy programs also tasked with developing new crafts or boats can be capitalized upon by consolidating their simulation needs. What may appear prohibitive from a cost standpoint for a single Navy program such as the AALC development, may become quite feasible and attractive when capital investment and overhead costs can be advantageously shared.

Major lessons from the history of the DSRV and hydrofoil simulations are applicable to the current Navy programs in need of simulation and in particular to the AALC program.

The ACV's high speed and open sea maneuvering requirements render the ACV simulation somewhat similar to the hydrofoil one. The ACV docking requirement on the other hand, with its need for fine attitude alignment and one foot lateral position accuracy, render the ACV simulation requirement somewhat similar to the DSRV simulation. Meanwhile, the man-in-the-loop problems and their impact on the ACV design are specific to the AALC objectives. In developing new high performance crafts, simulation plays a vital role unlike in previous high displacement ship designs. The high speed, short time constants and multi-control option render an explicit man-in-the-loop simulation extremely useful if not necessary. One might argue that the man-in-the-loop problems can be solved without a simulator by later additions of "black box" controls. It is felt however that the postponing of specific man-in-the-loop studies is not justified. The ACV control problems involve closed loops where the man-machine interface is only one of the links. The adequacy of sizes and vectoring capabilities of effectors should be studied on a simulator as soon as possible in order to assess the maneuverability and operability of the craft.

Items as diverse as adequate cockpit design, definition of safe operational envelopes, failure mode analyses, etc., can only be approximated without a simulator. It is felt that safety considerations and the need for allowing low skill personnel to operate the craft demand that a more complete system evaluation be performed on a simulator with explicit man-in-the-loop features. It is a good policy to preempt ahead of time the largest number of potential problems in order to allow for their timely alleviations.

## 2.4 Use of Simulation in a Navy Vehicle Development

Figure 2-1 is a compilation of simulation uses for a typical Navy craft development program. This figure suggests that Simulation is an explicit activity in a network of activities that make up the development and acquisition of a new craft (only one subsystem is shown). Some activity flows are inherently "one way" while others are iterative. The following sections elaborate on the role of simulations in various developmental phases as might be applicable to an ACV.

### A. Subsystem Design Using a Simulator

While many subsystem designs can proceed iteratively without explicit computer simulation support, some ACV subsystems such as the lift and propulsion devices, the controls and the pilot (the human operator is a legitimate subsystem) would require it. Stability and maneuvering characteristics or other performance data may be rendered by simulation in successive, iterative design attempts, yielding performance information to bring improvements in the next iteration step. These simulations can take the form of captive or non-captive scale models (true analog) or the form of mathematical representations implemented on a computer. Although the design of a craft control system is what ordinarily justifies the starting of a computer simulation effort, the ACV subsystem design support activities could have been important from the outset if a sophisticated simulator had been available. For the current AALC program at its present stage of development, the importance and need for explicit dynamic simulation is not equal for all subsystems. Since most of the current ACV subsystems are already designed, at least on the preliminary level, the iterative design support aspect of the simulation would be somewhat limited for certain subsystems. However, it is felt that for both the Bell and Aerojet ACV configurations that a substantial amount of work remains to be done by means of a realistic simulator in the following areas:

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Figure 2-1  Use of Simulation in a Navy Vehicle Development

validation of design and definition of performance envelopes for the effectors (size of effectors, effect of speed and winds, stopping distance and maneuvering characteristics) and the control system (cockpit design, actuators and displays, automatic feedbacks, man-machine interfaces). Failure mode analyses should be conducted using the man-in-the-loop simulator, explicitly accounting for man-in-the-loop time constants and idiosyncracies. This is particularly important for ACV's where many control options are available to the pilot, and the craft time constants are relatively short. A simulator can also detect sensitivities of a craft dynamic characteristics to certain parameters. The specific sensitivities uncovered by a simulator can be used for better planning of scale model testing.

B. Subsystem Implementation Using a Simulator

When prototype elements of a subsystem, such as hydraulic controls, electronic autopilots, or even lift fan and other effectors, become available a real-time marriage to a simulator may constitute an excellent test bench for certifying and checking these elements. Reliability and adequacy can be evaluated early. If a software package has to be developed for instance for an autopilot, or a monitoring mini-computer for a data acquisition system to be used during sea trials, the simulator support becomes invaluable in saving time and costly utilization of all prototype systems in their final configuration.

C. Test and Integration Using a Simulator

A real-time simulator background to integrate subsystems into their final configuration may be extremely useful. A particular example should be the integrations of the ACV cockpit and controls, with man-in-the-loop, and simulated power plant and effectors, enabling an orderly development without mobilizing a large logistics of actual craft systems. Substantial time and cost can thus be saved.

D. Supporting Full Scale Trials with a Simulator

A simulator should be used to "run" the ACV sea trial maneuvers ahead of actual operations. Performance and references can be obtained to serve as acceptance criteria for craft buy-off by the Navy, while marginal, unsafe or potentially catastrophic maneuvers can be predicted (ACV turning in waves, yawing while negotiating surf, maneuvering close to obstacles, and maneuvering in formation).

E.  Full Scale Data Acquisition - Use of a Simulator

The usefulness of the full scale trial data is not only a function of the
accuracy and efficiency of the data acquisition system, but also of the
techniques adopted for reduction and analysis of the data.  Statistical
analysis is best performed by computer processing - and should bene-
fit from the hydrofoil experience.  A great deal of the information to
be extracted from the ACV full scale data, however, is not statistical
in nature and resorts to careful time-domain extractions of vehicle
responses: rise-time of the effectors, response time of the craft,
stability and couplings as functions of speed and cushion gap, stopping
distances and turning radii, etc.  The analysis of the data should pro-
vide the effective coefficient values for the equations of motion by
appropriate solution of the "inverse problem", i.e., the problem of
extracting hydrodynamic and other coefficients from actual flight data.
(See Appendix C.)  The ACV computer simulation can then be updated
to reflect actual full scale craft behavior - and thus improve its pre-
diction reliability.  (It should be noted that "inverse problem" tech-
niques can also be used with non-captive or partially captive scale
model tests.)  It will be shown in Appendix C that a computer simula-
tion can be used as an explicit tool to participate in the solution to the
"inverse problem" since iterative, converging identification techniques
usually demand some sort of a computer model.


2.5    Need Sophistication Level for an ACV Simulator

It is axiomatic that simulation results are not more realistic or useful
than what is potentially allowed by the mathematical modelling upon which
the simulator is based.  In the case of the DSRV, an inch-like positioning
accuracy in docking could be simulated only if all relevant interactions
were modelled; in particular, roll-surge couplings, nonlinear drag, in-
duced drag and environmental "suction" forces when docking occurred in
a current.  The desire for accurate modelling prompted the derivation of
sophisticated DSRV equations of motion with numerous experimental data
correlation.  For the ACV simulation, the requirement for docking to
and unloading from the stern of a moving mother ship and the requirement
for alongside maneuvering in a seaway dictate extreme caution in the
derivation and simplification of the equations of motion.  "Proximity"
hydrodynamics (wake) and aerodynamics (turbulence, wind shadow, air
flow deflection and restriction) when the ACV approaches a target ship

should be modelled if the simulation objective is to investigate the craft controllability under these close formation conditions and to assess the ACV system ability to meet the one foot lateral accuracy requirement when docking. In docking situations, the ACV-LSD-seaway is a dynamic system to be brought under reasonable equilibrium. Major components of drag, whatever their origin, should be balanced by corresponding "bias" components of thrusting by the craft effectors. Incremental thrusts and yawing moments must be initiated by the pilot through the cockpit controls in judicious amounts to effect the desired sway-yaw alignment as well as the terminal docking. The delicate balance of bias and incremental components of effector actions with the craft drag and external forces and excitation is what the simulator is trying to render  The size of incremental thrust compared to the craft inertia and the target motion will determine the time constants of the docking maneuvers. The pilot will have to adapt himself to these time constants and provide, by visual perception and operation of the controls, the stable, damped closed-loop behavior desirable in terminal maneuvers. It is clear that the simulated dynamical balance of forces and moments should reflect all contributing items. Oversimplification of the air cushion hydrodynamics, for instance, could lead to ignoring or misaccounting sizable horizontal forces during forward or lateral maneuvering. Since it is expected that lateral forces generated by the water surface underneath the ACV may be of the same order of magnitude as the incremental forces initiated by the pilot during a turning or docking maneuver, it is desirable that the simulator performs a thorough budgeting of all interactions, not only the dynamic, hydrodynamic, aerodynamic ones, but also of the visual inputs into the pilot and the latter's actions.

2.6  Specificity and Adaptability of Simulators

Since the craft simulator of interest here involves the computer translation of mathematical design definitions, it is important to consider the manner in which the input data portraying the simulated craft is organized and obtained. For assessing the usefulness of any craft motion simulator, it is crucial to consider the following distinction:

A.  Simulation from Non-Structured and Lumped Data

Example :  Lumped drag coefficients, obtained from model testing, enter the equations of motion.

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## B. Simulation from Structured and Non-Lumped Data

Example : Location of C.G. and sizing of inertial
tensor by explicit accounting of weight
distribution.

For many simulation objectives, a non-structured or lumped data approach
to modelling is sufficient[*]. For other situations, however, especially in
iterative craft design using simulation, it is important to resort to a struc-
tured approach since one wants to investigate the effect of single or multiple
parameter changes. While straightforward for items such as weight distri-
bution, position, size and direction of thrusters and effectors, control
settings, etc., the obtainment of structured mathematical models is difficult
or almost impossible for other features: drag prediction for a given ACV
skirt design and geometry; detailed and quantitative impact of skirt com-
partmentation and lift control on drag and stability; beam-to-length ratio
on hydrodynamic and maneuvering characteristics; proximity to hump speed
(below and above) and time history dependence of the wake pattern, etc.

The inability to easily or directly relate physical or geometric design
definitions to some craft or boat characteristic and the difficulty to clearly
and quantitatively unravel the factors contributing to a final performance
are at the heart of the modelling problem. These elusive but important
craft characteristics are usually estimated for a given vehicle configuration
through scale model testing. If enough different configurations (different
skirts, different beam-to-length ratios, in general; vary one subsystem
parameter keeping all others constant) have been tested by scale models
with appropriate non-dimensional characterization, a trend behavior can
be surmised by interpolation or extrapolation. The model test data can
then enter the computer simulation in structured tables. It is clear that
such a multiple-scale-model-test approach can easily become very expensive.
And yet it is also clear that an important characteristic of a Naval craft
simulation is its ability to readily reflect in motion prediction and other
performance factors the impact of design changes or variations. It is

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[*] Note: The hull hydrodynamics of DSRV entering the DSRV simulation
was completely "unstructured". Since the simulation purpose was to
develop the sensors and controls, and not to design the DSRV hull and
appendages, this seemed adequate. However, recent sea trail experi-
ence indicates that the DSRV is substantially less directionally stable
than expected. This is not necessarily a poor feature for a rescue
boat since maneuverability is enhanced. However, for other mission
objectives such as search, inherent directional stability is crucial. It
is felt that a structured hydrodynamic modelling in the equations of
motion would have helped in predicting this important phenomenon.

axiomatic that the greater this ability is, the greater the usefulness of the
simulator when used for creative design. The logical conclusion then is
to attempt to model as much as possible the complicated physical laws that
link craft parameters (skirt design, beam-to-length ratios, etc.) to observed
dynamic behavior, i.e., drag, stability, maneuverability, etc.

Chapter 3 will elaborate on this subject, but it suffices here to say that the
implication for ACV's is a sophisticated modelling of the water surface
underneath the air cushion. Clearly here the cost instead of being in model
testing will be in analysis manpower and in an adequate computer facility.
It is MIT's contention that these costs are well worthwhile, since analysis
manpower cost is a one time occurrance that will put ACV understanding
and technology on a sounder footing, while an adequate computer facility
is a necessary capital investment to be amortized over the years and hope-
fully to be shared with other Navy programs.

The needed degree of sophistication in the modelling involved in a craft
simulation depends on the specific objectives. Simple lumped parameter
models are sufficient for many purposes such as: crew training, design
and implementation of "black box" control systems, design and imple-
mentation of data acquisition, extraction of coefficients from actual trial
data using "inverse problem" techniques, etc. For other detailed studies,
the modelling sophistication may have to be quite substantial. For sub-
marines operating near the surface, there would be a requirement to
carefully model suction forces as a function of sea-state, depth and motion.
For ACV's, the model would have to simulate sudden craft acceleration
or decelerations, man-in-the-loop approach to a target, travelling through
surf, maneuvering through waves, etc.

In general, a flexible approach to modelling should be used: The sophis-
tication of the various building blocks must be subordinated to the overall
computer constraint. If the computer is fast enough and big enough to
accommodate complicated programs, these might as well as be adopted.
The quest for increasing modelling sophistication will, however, soon reach
the computer speed or core saturation. At that point many ingenious
schemes can be generated, for instance, by trading core for speed, or by
allocating computer throughput to the task at hand while decreasing the
modelling sophistication of other marginal subsystems to more cursory
forms. The flexible allocation of computer throughput resources as a
function of the simulation objectives at hand was often made at MIT. For
the DSRV simulation, it is believed that the relatively low computer speed
and moderate throughput capacity was, although taxed to the limit, made

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acceptable by careful segmentation of programs and organization of duty cycle. For instance, a complete simulation of the DSRV propulsion with modelling of the motor speed controller nonlinear torque characteristic was effected. Peak electrical current loading and other idiosyncracies were investigated. However, when such investigations were proceeding, no sonar and no man-in-the-loop simulation could be conducted concurrently because of the computer speed saturation. Several similar situations may occur within the framework of an ACV simulation. MIT stresses the fact that a model for a subsystem may not be applicable for all simulation objectives when several subsystem models compete for a limited throughput capacity. It is important to evaluate how much realism is lost in retailoring the model's sophistication to accommodate the throughput constraint. Good engineering judgement should guide one in deciding whether the loss in realism is acceptable to initiate the simulation task or give credence to its output.

2.7    The Components of a Naval Simulation Facility for ACV's and other Crafts or Boats

There are three major components to an ACV craft motion simulator:

1.  The mathematical models rendering the dynamic, hydrodynamic and aerodynamic phenomena of an ACV, its effectors and its environment.

2.  The real-time computing system which will translate the mathematical model into instantaneous interactions under the stimuli of initial conditions, control commands or environmental disturbances of waves, winds or surf.

3.  The man-in-the-loop simulation equipment:

    a.  The video and projection equipment for rendering the optical perception from the cockpit.

    b.  The movable platform with actuating hydrodynamics and servomotors needed for the kinesthetic simulation.

    c.  The actual or mock-up ACV man-machine interfaces, such as cockpit with displays and controls.

Figure 2-2 is a conceptual diagram of activities leading to end-item procurement for an ACV simulator.
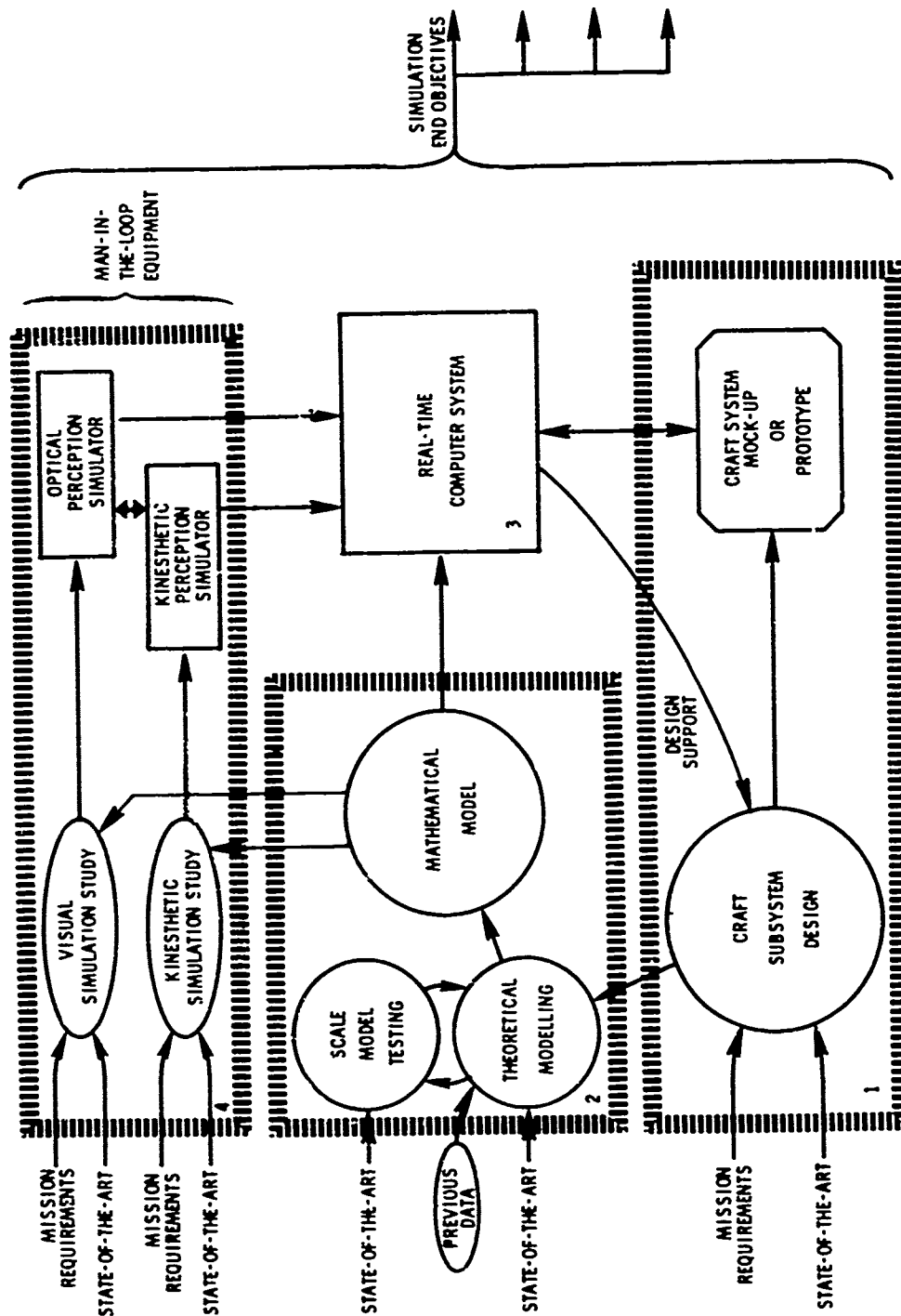
Figure 2-2  Procurement of an ACV CraftMotion Simulator

A careful evaluation of each activity item as applicable to an ACV was necessary before reaching the conclusion and recommendations of the following three chapters. It is apparent that responsibilities for the items numbered on Figure 2-2 are ascribed to

1. both AALC contractors,

2. an analysis group selected by the Navy,

3. a yet to be defined Naval Simulation Facility, probably shared with other Navy programs and operating in an "open" or "closed" shop fashion (see Chapter 5), and

4. an agency to be selected by the Navy.

CHAPTER 3

MATHEMATICAL MODELLING
OF AIR CUSHION VEHICLES

3.1    Summary and Conclusion of Chapter

MIT has reviewed the available literature on ACV's and the design docu-
ments of both Bell Aerospace and Aerojet General, the two AALC con-
tractors. The state-of-the-art in free surface hydrodynamics has been
carefully looked at since it is at the heart of the ACV motion modelling.
A mathematical modelling was aimed at fitting the constraints of a reason-
ably sophisticated computer simulation of an ACV over the surface of the
ocean.

The primary objective is to formulate a method which will give traject  es
and orientation of the vehicle as a function of time. The calculations re-
quired must be of sufficient simplicity to allow predictions in a real time
simulation and yet give a valid representation of the results. There is no
attempt made to advance the state-of-the-art in the fundamental dynamics
involved, but only to chose and build on exisiting, if recent, techniques
for prediction of forces, moments, trajectories, and motions. Rather
brutal simplifications and linearizations must be made where MIT/Draper
Laboratory feels that they are necessary and justified in reducing the
problem to the feasible level. Every effort has been made to point out
where, why, and how, simplifications have been made and the loss of
generality and validity caused by these simplifications. This chapter is
intended as a guide or route map for the engineers and programmers who
will execute the ACV simulation outlined here. Attempts are made to point
out and document alternative approaches which are available and which the
eventual executors of the simulation project might prefer. This is a
description of one possible approach to the problem. It is most certainly
not the only and perhaps not even the best way to do it.

A great deal of the material herein concentrates on approaches to the
analysis of the effect of free surface hydrodynamics on the problem. The
reason for this is that it is felt that the work done by Aerojet General and

Bell Aerospace on the other aspects of the problem such as thruster and control errors, skirt drag, momentum drag from turning air flow, aerodynamic drag, etc., is sufficient and considering the rather primitive state of the free surface hydrodynamic calculations probably far more than sufficient for the final motions and trajectory calculations.

In conclusion, MIT recommends two approaches for the hydrodynamic modelling of ACV's: First, a low risk, moderate return approach based on classical "amnesic" equations of motion, involving standard, if repetitious and lengthy, scale model data. Second, a higher risk, higher return approach based on distributed modelling of the free surface and its interaction with cushion pressure and craft maneuvering, in the line of rec    studies by Doctors and Sharma (University of Michigan) and T.K.S. M .thy (University of South......pton, U.K.)[1] [2]

Each approach requires an analytical effort coupled with scale model experimental derivations and/or correlations. The first approach is straightforward although tedious in implementation; by its nature it is quasi-steady and unable to properly predict transient cushion and wake phenomenon. The second approach is developmental but offers great promise. Appendix A gives cost estimates and details on these plans.

## 3.2    Derivations of Equations of Motion

### 3.2.1    Importance of the Free Surface Phenomena

A rough idea of the importance of the wave hydrodynamics may be gained from Figures 1, from Doctors and Sharma (Reference 1) showing the resistance versus thrust breakdown of an air cushion vehicle accelerating under constant thrust. The wave resistance is a significant fraction of the total and it must be stressed, as pointed out by the authors, that a quasi-steady analysis using resistance from constant speed towing tank results is not sufficient for the prediction of maneuvers, particularly involving large accelerations at speeds near hump speed. The unsteady or acceleration-dependent wave resistance (or as the authors call it "dynamic sustention power") is important and calculable, and should be included in the mathematical model. In some cases, as pointed out by Doctors and Sharma, an ACV that according to quasi-steady theory or experiment did not have enough power to exceed hump, might well be able to get over the hump in practice and a mathematical model including unsteady or acceleration-dependent wave forces is necessary to predict the performace. An inexcusably simplified way of looking at this is that if the vehicle accelerates fast enough, it will

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not have time to generate the large waves corresponding to constant speed results for its instantaneous velocity. It is, therefore, essential to include unsteady hydrodynamic calculations in the mathematical modelling of the vehicle.

### 3.2.2 The "Maneuvering" and "Motion" Problems

There are two basic free surface hydrodynamic problems which must be dealt with in the ACV simulation model. One of these concerns the forces and moments exerted on the vehicle in previously calm water due to its motion in proceeding at constant velocity, perhaps at a yaw angle, or accelerating and turning. This type of motion comes under the general classification of "maneuvering" and will be referred to as such in this report. The other major hydrodynamic problem is the response of the vehicle to a seaway for an assumed nominal trajectory, usually a straight line. This is the Naval Architect's classical vehicle "motions" problem. A great deal of work has been done on both problems, as applicable to an ACV but the field is still quite new as far as practical applications and correlation between theory and experimental results either from model or full scale tests. In particular, when an ACV is turning in waves, a super-position of the "maneuvering" and "motion" problem occurs. During maneuvers such as approaching the mother ship well, coming alongside, rendezvousing for landing, proceeding in formation and avoiding collision, an ACV will encounter many combinations of seaway motion and maneuvering situations. It is mandatory that the simulation model accounts in a time domain sense for both types of input at once to investigate safety and tightness (minimum turning radii) of these maneuvers in waves, as well as the time constants and various cross-coupled motions inherent in them.

There are two fundamental approaches to approximating unsteady forces and motions of vehicles on the air-water interface. The most common one is briefly described below and for reasons that will soon become apparent is often referred to as the "amnesic" model, i.e., a model that does not remember everything that it ought to in order to yield a complete description of forces and moments and the resulting craft trajectory. A more rigorous model would encompass a detailed description of the water surface, usually by means of a potential function; the distributed pressure imposed by the ACV cushion shapes the water surface which in turn causes forces and moments on the craft. An explicit accounting of craft sudden acceleration or deceleration, yawing or heaving can be "microscopically" modelled by proper working of boundary conditions for the distributed

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models and proper dynamic interactions.

## Amnesic Modelling of Craft Motion and Maneuvering

The most common procedure is to expand all forces in terms of Taylor
series of motion coordinates and derivatives about an equilibrium condition
and retain terms of high enough order to give sufficiently accurate results
without excessive computation time. Most ship motions, and for that mat-
ter ACV motions, work is based on this approach, and particularly if mo-
tions are small, a cutoff of the Taylor expansion after the first order
terms is often sufficient to yield the results to the accuracy necessary.

In maneuvering analysis the Naval Architects have found it necessary to
carry their analysis to the third order terms in the Taylor series expansion
of restoring and control forces (Mandel [3]) to obtain sufficient accuracy
for tight maneuver predictions. There are, of course, important differences
between the ship and the ACV maneuvering problems. The two critical
differences are 1) that the ACV operates a large fraction of the time at
yaw or leeway angles that would be unusual for a ship, and 2) that the hydro-
dynamic problem, assuming that skirt immersion is treated separately
and does not couple with the surface pressure and profile description, is
far simpler than the surface ship problem. The surface ship at an angle
of attack is an analytical jungle with high viscous drag, separation and
waves to contend with. The air cushion vehicle is still a pressure distri-
bution, although no longer symmetrical as in straight ahead motion, and
there is reasonable hope for an analytic or semi-analytic modelling.

The following sections address themselves to the ACV modelling problem
segmented in "restoring" and "exciting" forces. This subdivision is logi-
cal and corresponds to the "autonomous" and "non-autonomous" part of the
ACV-Ocean coupled dynamics. Restoring forces act on the ACV whenever
an initial condition off the equilibrium point is somehow created, indepen-
dent of the presence of external excitations.

## 3.3 Modelling of Linear and Nonlinear Restoring Forces

For an approximation to the equations of motion suitable for simulation
of the ACV, the dynamic characteristics of the vehicle itself must be known
with some accuracy. There are several methods for the vehicle dynamic
characteristics, both experimental and analytical. This section discusses

the analytical approaches suggested for estimating the dynamic character-
istics.

It is suggested that the problem be split into two parts as is generally done
in ship hydrodynamics, namely into restoring forces and exciting forces,
and that linearization of the problem be carried as far as possible. For
this purpose, restoring forces will be defined as those forces required to
give the ACV prescribed motion in calm water. Exciting forces are de-
fined as forces from waves, disturbances, such as a ship's wake, wind,
surf, and controls.

The first consequence of linearization which must be borne in mind is that
exciting forces will be considered to act as if the ship were in its mean
position. In other words, the effect of the vehicle motion on the exciting
forces is considered small. Some alterations to this premise may have to
be made for effects such as wave impact and skirt drag, but the basic
structure of the analysis will make this assumption.

The restoring forces are analyzed separately and are associated entirely
with the motion of the vehicle. If the exciting forces on a restrained
vehicle are k      n and the restoring forces for the vehicle moving in calm
water are kn.  ; the motion may be obtained by summing these and setting
the result equal to zero.

For ship motions work, this type of analysis is generally done in the fre-
quency domain making the assumption that output is proportional to input
and that results may be superimposed. It is assumed that the ACV simu-
lation will be time domain and that calculations will be done within real
time. The basic analysis for motions due to seaway excitation is, however,
still applicable but must be amended for various aspects of this particular
problem. The most critical limitation of linear modelling occurs in the
description of tight and involved maneuvers. In surface ship maneuvering
predictions it has been found necessary to carry the Taylor series ex-
pansions for the restoring forces out to the third derivative to obtain
accurate trajectories. The reason for this difficult type of analysis is the
sophisticated geometry boundary conditions, viscous forces and separation
effects that are important on a surface ship. The ACV problem is, at least
as far as free surface hydrodynamics are concerned, somewhat simpler
than the surface ship. The boundary condition on the water surface is on
pressure rather than on normal velocity, in other words, the boundary
condition is on pressure all over the free surface both within and external
to the region of the vehicle.

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In all considerations of the hydrodynamic characteristics of the vehicle it
will be assumed that the free surface conditions may be linearized. This
implies that wave slopes are small enough so that the perturbation velocity
squared terms in Bernoulli's equation may be ignored and that the kinematic
condition may be linearized. The basic assumption here is that wave slope
is small which is reasonable for the ACV except at hump speed. There
are indications (Doctors [1]) that if hump speed is approached and passed
through quickly, the large and steep waves observed in constant speed
tests will not occur.

The magnitude and direction of the hydrodynamic free surface restoring
forces are most easily visualized in the following manner. Consider an
ACV running over smooth pavement as in the sketch below.
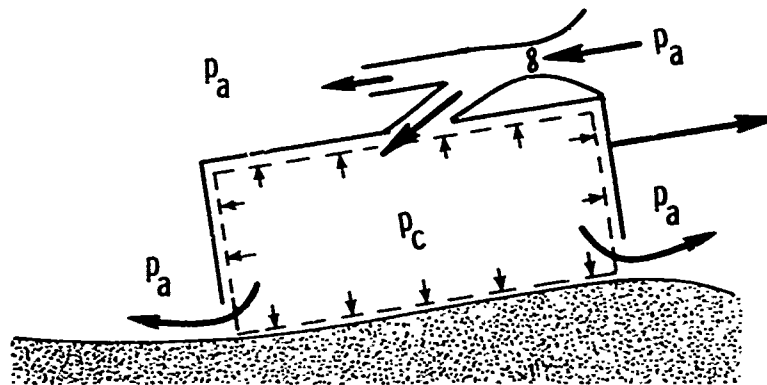


The forces acting on the vehicle due to the pavement are of three types:

1. There is a change of momentum of the air as it passes through
   the thruster and plenum fan and out under the skirts. This
   effect has been accounted for by all investigators in one way
   or another.

2. There is a force on the vehicle due to the pressure $p_c$ on the
   base of the dotted control volume drawn. This effect may be
   obtained by integrating air pressure along the inside of the
   skirt and underside of the structure but this seems a round-
   about approach. The fact of the matter is that the pressure
   force is normal to the surface of the pavement, assuming that
   pressures are normal only or that shear between the plenum

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air and the pavement is negligible. (Any investigator who attempted to include shear between air and pavement would be running extreme danger of mathematical indigestion.) The major essential point here is that the local pressure force on the bottom of the dotted line is normal to the pavement. If the pavement were not flat and level (waves), the pressure force would still be normal to it locally, which makes it vital to know the shape of the pavement. The pressure distribution ($p_c$) is altered by the presence and shape of the pavement. This is a matter of fan, duct and plenum or bag characteristics and skirt clearances and is taken account of in most analyses.

The major question which has bot been fully explored in motion prediction of ACV's over water is the question of the shape of the pavement (water surface) under the vehicle. If a simple direct answer could be given to that question, the computer simulation of ACV's would be reduced to a straightforward if tedious task.

3.  There may be contact between the skirts and the surface below, leading to viscous drag, impact forces, and mathematical complexity. This is a situation which both designers and analysts do their utmost to avoid, but unfortunately it happens. These effects may only be approximated in the simulation by assumptions of drag coefficients and momentum changes.

The forces described in 1 and 3 above are treated in some detail by Bell and Aerojet (Reference 4, 5), but the wave hydrodynamic forces described in 2 have been the major stumbling block of all ACV motions studies to the present time. The first large effect is that of wave drag in steady, straight ahead motion. A sketch of the situation in the fore and aft longitudinal plane is shown below.
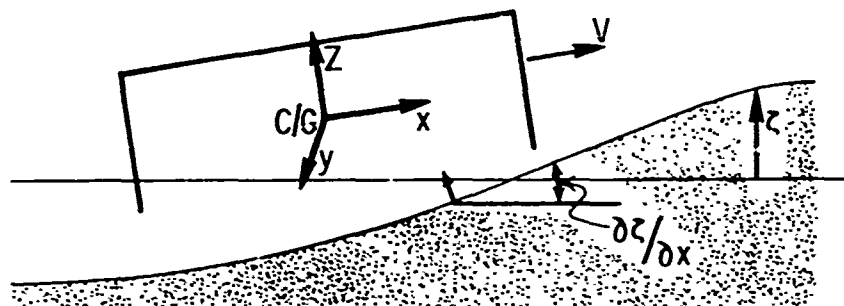
The wave drag in such a situation may be described by:

$$D_w = \iint_{\substack{\text{cushion} \\ \text{area}}} p_c(x, y) \frac{d\zeta}{dx} \, dx \, dy$$

•where $\zeta$ is the water elevation above undisturbed water level and the integral is taken over the area under the cushion. It is assumed in this approach that vertical pressure gradients in the air cushion are small and that therefore the pressure on the water surface is equal to the pressure in the cushion above. The problem is of course, to find $\zeta$, the water surface description and $p_c$, the air pressure in the cushion. The ACV manufacturers (Bell and Aerojet) have done a great deal of work on the determination of $p_c$, the air pressure, but the water surface elevation is quite another story. Models of the free surface description and forces resulting from a pressure distribution started with Havelock [6] and have been dealt with by essentially every ship hydrodynamicist since. The state-of-the-art is summarized by Doctors and Sharma or Murthy. The straight ahead motion of a symmetrical vehicle moving at constant speed is well defined and the wave elevation beneath such a vehicle is derivable within the context of linearized surface conditions and source, sink, or dipole representations. Bell and Aerojet have access to $\varepsilon$      techniques and computer programs, although neither has devoted a major effort to implementing such procedures as it is not part of their primary task which is to design and build crafts. However, the possibilites of putting such techniques into action with modern computational facilities and a devoted programming effort are inviting. It is obvious from the a' ·ve that not only wave drag but wave forces and moments is all six degrees of freedom may be obtained if the surface profile and cushion air pressure distributions are known. The importance of this approach to a valid simulation may be stressed by the following example. Let us assume that the craft is in steady, straight ahead motion over the water surface and that the thrust is obtained by air propellers above the hull. Assume that the vehicle has pitch stability due to compartmentation or bow and stern air bags. If the air propeller were moved higher on the vehicle and the water surface were rigid (pavement), it is obvious that the bow would pitch down until the pressure in the forward half increased enough to hold the craft in pitch equilibrium. Water, however, is not rigid and the effect is far more subtle. The vehicle must still pitch down relative to the water surface to increase pressure in the forward half.

This change in the pressure ($p_c$) distribution, however, changes the wave surface profile and may cause the wave elevation to increase markedly at the bow. This means that the bow moves up and may move up more with the water than it moved down relative to the water. The results of a first order theory by Murthy indicate that the general effect of moving the thrust line up is to cause pitch up motion at the bow. It seems obvious from these two rather simple examples, straight ahead steady drag and pitch equilibrium, that a simulation model which neglects the deformation of the water surface is not going to get very far.

Assuming that a source-sink or dipole potential flow represensation is possible for the water dynamics in straight-ahead constant speed motion, it is tempting to assume that the problem is solved. On further examination, however, it appears that our troubles are only beginning. We are interested in predicting the orientation and trajectory of a high speed ACV during radical maneuvers and changes in thrust magnitude and direction. The first complication that comes to mind is that an assumption of port-starboard symmetry with respect to the instantaneous direction of motion is unacceptable. The craft will be operating at large yaw angles when we are most interested in what it is doing. The mathematical model must not make assumptions of symmetry or linearize yaw moment derivations about straight ahead zero yaw angle conditions. The other more serious difficulty is that in maneuvering the problem is no longer steady in the vehicle reference frame. This is a problem which is encountered in surface ship motions and maneuvering and even in airplane simulations. Theories and computer programs exist for predicting pieces of the unsteady problems such as unsteady lift on foils, added mass of ocean vehicles (which is frequency or wave length dependent in the case of surface ships), wave damping, etc. Our problem in the ACV is in some respects simpler and in some respects more sophisticated than the surface ship.

Major factors in the displacement surface ship maneuvering problem are these:

1. The basic boundary condition is that the water flow must be tangent to the hull plating. This means that the boundary condition is on velocity at the hull surface and on pressure (atmospheric) elsewhere on the water surface. In other words, the boundary conditions are mixed (Neuman Problem).

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2.  The surface ship moving at a yaw angle is likely to experience
    a great deal of boundary layer and form (or separation) drag.
    A large fraction of total energy loss to the water is due to
    this rather than wave generation.

3.  The surface ship maneuvers rather slowly so that a quasi-
    steady analysis with the inclusion of few approximate un-
    steady terms such as constant added mass coefficient and
    added moment of inertia coefficient is acceptable.

In contrast, the ACV characteristics are quite different particularly in the
following respects:

1.  The basic boundary condition is that the pressure on the surface
    of the water under the vehicle is the air pressure from the
    compartments above.  In other words, if skirt contact is as-
    sumed not to occur for the moment, the boundary condition
    is on pressure everywhere on the surface of the fluid.  This
    makes analytical work far more feasible for ACVs than for
    surface ships (Dirichlet Problem).

2.  The effects of viscous resistance and separation are small
    unless the skirts contact the water, a problem which will be
    treated separately from wave forces.

3.  The speed is much higher and the maneuvers, particularly
    turning and accelerating, much more rapid than for displace-
    ment surface ships.  This fact introduces a myriad of mathe-
    matical difficulties.  Foremost among these is the dependence
    of the wave pattern under the vehicle not only on the instantan-
    eous velocity of the vehicle but on the recent past history of
    the motion.

3.3.1   The Amnesic versus Non-Amnesic Modelling Approach

The problem for thrust and drag is documented in a paper by Doctors
and Sharma, The Wave Resistance of an Air Cushion Vehicle in
Accelerated Motion [1] .  In this paper the instantaneous wave resistance
due to straight ahead motion of a pressure disturbance is calculated.  It
is pointed out that the wave configuration is very definitely a function of
previous velocity history and in fact that a vehicle accelerating rapidly
to hump speed and beyond may never experience the maximum wave re-
sistance predicted by constant-velocity (quasi-steady) analytical or ex-
perimental results.  The analysis approach employed in this paper is
effectively a determination of the velocity potential of the flow as a function
of the velocity history and pressure distribution (which is assumed con-
stant).  It is one dimensional in nature (surge only) but the possibility
exists for extension to other degrees of freedom.  Considerable experi-
mentation and programming effort are required to determine the numerical

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limits of this approach and to keep computer time within real time. Extension of this technique to more dramatic maneuvers such as slowing down quickly and being overtaken by one's own wave system has not been attempted, but should be looked into. No attempt has been made to extend this approach to other degrees of freedom or to an unsymmetrical pressure distribution (side slip) but the possibilities are inviting. This type of model would be similar to an instantaneous state model which includes an infinite number of terms in a time expansion series. In other words, the forces and moments would include not only terms proportional to velocity and acceleration but also terms in change of acceleration with time and all higher time derivatives. It seems likely that the convolution integral approach is simpler in programming and will lead to answers in less computer time.

An alternative approach, and one more familiar to ship motion and maneuvering analysis, is to ignore past history and assume that the forces on the vehicle due to its present motion are a function only of its present state. This is the approach usually employed for surface ship maneuvering analysis and for seaway motions prediction. Both contractors have made considerable progress in this direction in the course of developing turning radii, stopping distance and other results essential for design purposes. For a unified approach to a mathematical model of this type, the paper "A Linearized Potential Flow Theory for the Motions of Air Cushion Vehicles in a Seaway" (Reference 2) contains an excellent review of the state-of-the-art and a structure on which to build a computer model for both maneuvering and motions. The first order theory for pitch, heave, and surge is thoroughly worked out and the extension to six degrees of freedom is possible without great mathematical difficulty; extension to higher orders is possible but tedious. This technique works with an acceleration potential and dipole distribution for the pressure distribution at the bottom of the cushion. Various critical results such as side force during drift motion and pitch resonance effects come directly from this approach within the limits of the first order theory. The greatest advantage of this general approach is that it is the conventional method for ship maneuvering and motions analysis. Forces and moments are expressed in terms of coefficients, which in the case of oscillatory motion may be functions of frequency, of a Taylor series expansion in velocity and acceleration. For a basic description of this approach, the reader is referred to "Principles of Naval Architecture," [3] published by the the Society of Naval Architects and Marine Engineers, Marine Hydro-

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dynamics by J.N. Newman[7] or Stability and Control of Ocean Vehicles by M.A. Abkowitz[8]. Newman also points out in the above text the basic breakdown of the amnesic model when considering motions and forces on the free surface. Further background is contained in a paper by Newman, "Some Hydrodynamic Aspects of Ship Maneuverability"[9] based on work by Hasking, Cummins, and Brard. The traditional amnesic model considers the ship to be basically a second order six-degrees-of-freedom system. When the equations of motion are linearized all restoring forces are considered to be proportional to velocity and acceleration in the six degrees of freedom. For maneuvering analysis the proportionability constants are assumed to be independent of history or frequency. For ship motions analysis the coefficients are allowed to become functions of frequency. As long as the motion is sinusoidal in time or if the motion is periodic and can be broken up into frequency components, this analysis is valid and useful assuming linearity so that frequency components may be superimposed. The possibility exists of extending this approach by Fourier integral techniques for a more valid representation of transient effects. However, if it is decided to include such effects, it is suggested that the time domain convolution integral approach described previously be used because nonlinear effects may be included by extending the Taylor series to product terms and higher powers in velocity and acceleration. The ACV operates frequently at larger yaw angles than would normally be encountered on a surface ship maneuvering. This means that higher terms must be included in the analysis, particularly for side force and yaw moment that are usually used in surface ship predictions. Very possibly it would be more efficient to do the analysis to lower order at discrete sideslip angles and use the Taylor series approach for interpolation between discrete conditions. Again the basically transient nature of the problem is stressed since the side force and moment for turning are achieved at a cost in thrust.

The coefficients in the linear or even nonlinear amnesic equations of motion have the advantage of being readily verifiable by standard planar motion and rotating arm model techniques.

A fundamental decision must be made to either initiate hydrodynamic and programming effort into the potentially valuable time domain approach to the wave hydrodynamic problem or to continue with attempts to fit the traditional amnesic Taylor series ACV model.

## 3.4 Modelling of ACV Exciting Forces

The forces acting on the vehicle due to the external environment such as seaway excitation, wind excitation and the wakes of other crafts are considered as "exciting forces". Above and beyond these effects, the forces exerted by control and propulsion devices will be considered exciting forces as well. The most critical exciting force for the safety and useability of ACV's is the seaway excitation. Particularly for close maneuvering at high speed, wave excitation may be the limiting parameter on safe operation. A representative model of a realistic seaway is vital to this simulation both for calculations and model testing and is presented below.

### 3.4.1 Seaway – ACV Interaction

The force acting on the vehicle due to the seaway is transmitted in several ways. First the shape of the water surface beneath the vehicle is altered by the wave profile. It will be assumed, however, that the pressure distribution of the cushion does not affect the wave itself. In other words, waves are not diffracted by the vehicle. This assumption that the incoming wave system is not altered by the presence of the air pressure distribution is somewhat reminiscent of the Froude-Kriloff condition in ship motions analysis. It should be applicable in the ACV work than for displacement ships since the normal velocity hull plating boundary condition need not be satisfied or ignored. Note that this assumption does not imply that waves are not made or that the surface is deformed by the vehicle. The vehicle makes it own waves due ' its moving pressure distribution as covered above under "restoring forces".

The total disturbance or surface deformation beneath the vehicle is that due to the pressure distribution of the vehicle plus that due to the incoming waves. It may be found advantageous by the final simulation programmer to add wave profiles rather than separating into exciting forces and restoring forces at this point. For example, referring back to restoring forces the wave drag is

$$\iint_{\substack{\text{cushion} \\ \text{base}}} p_c(x, y) \left(\frac{\partial \zeta}{\partial x}\right) dx\, dy$$

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where $\zeta$ is the surface equation due to the cushion pressure distribution. Similarly and by the same reasoning the force in the -x direction due to incoming waves is

$$\iint\limits_{\substack{\text{cushion} \\ \text{base}}} p_c(x, y) \left(\frac{\partial \zeta_w}{\partial x}\right) dx\, dy$$

where $\zeta_w$ is the surface elevation of the incoming wave pattern beneath the vehicle. Separation is necessary for purposes of analysis and experiments of the following two types:

1. Derivation of restoring force wave drag by moving, accelerating, or maneuvering the vehicle through previously calm water.

2. Derivation of exciting forces by holding the vehicle still and measuring the force due to incoming waves.

It is simplest conceptually and essentially practically to separate the integrals above for derivation and experiments of the sort above. However, for the final simulation it will obviously save computer time to combine the integrals as follows:

$$\begin{array}{c}\text{Total wave force} \\ \text{in -x direction}\end{array} = \iint\limits_{\substack{\text{cushion} \\ \text{base}}} p_c(x,y) \frac{\partial \zeta}{\partial x} \left[\zeta + \zeta_w\right] dy\, dx$$

Similarly, for the determination of skirt gap or contact with the water surface, it makes sense to use the combined surface profile. The impact and drag forces exerted on the ACV by the skirt contact with the water surface constitute another important class of "exciting" force.

### 3.4.2 Seaway Modelling

Having defined the mathematics of the transmission of forces and moments from the water surface to the ACV, it remains to describe the water surface in two important cases: an agitated seaway and a surf zone.

### 3.4.2.1 Modelling of a Seaway

An ocean wave state is basically a statistical phenomenon. There is delusion involved in any deterministic modelling of the seaway for this reason. If the deterministic representation 's a discrete frequency model, care must be taken to include the frequency range of particular interest

to the problem, and to space the excitation closely enough in frequency so that resonances are not missed. If the model whose response is being studied is stationary or moving at extremely low speed compared to wave phase velocities, care must be taken to vary the phase of input components so that the vehicle will not see repetitions of the same wave form. At higher speed this is not a problem, assuming that dispersion effects are properly included in the model. It is for these reasons that a seaway representation has been generated in the MIT Department of Ocean Engineering towing tank by running random numbers through a seaway filter to drive the wave paddle. The tank itself serves as an analog computer to correctly account for dispersion and frequency of encounter effects. Assuming that in the contemplated ACV simulation we will not be operating with as convenient an analog as a towing tank and that correlation between what the craft feels and what the operator sees must be accomplished by other straightforward techniques, the discrete frequency deterministic model is recommended for this problem since the surface elevation and velocity of each component as a function of water depth may be described analytically. It is assumed herein that whatever display man-in-the-loop operator sees the sea surface on is computer rather than mechanically driven, since dispersion of waves is difficult to model mechanically without including an actual water free surface in the simulation.

The other basic problem in seaway modelling is the question of how to represent the directionality of the seaway. For towing tank purposes the seaway is usually considered nondirectional or equivalently "long crested". Analytical and computer modelling of ship motions are also commonly done by nondirectional techniques. However in the ACV simulation we are primarily interested in the description of the water surface beneath the vehicle as a function of time rather than a frequency domain model with exciting and restoring forces as a function of amplitude and frequency. This comment is independent of the decision regarding amnesic or convolution integral techniques since in either case the exciting forces will be derived analytically from consideration of the surface profile. It is not a great extension either conceptually or practically to include seaway components from various directions and within the limits of linear superposition of surface waves, to obtain a time domain description of the irregular sea surface. Multi-directionality is, however, in a certain sense a luxury in the simulation effort and the number of different directional components must be considered on the basis of how much computer time and storage is available. It is recommended that at least two directions

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be included to simulate the short-crested phenomenon and that more be added if possible.

An alternative approach, if computer time and space are tight, is to vary the amplitude of each component of the unidirectional sea in the direction along the wave crest. This may be done in computer time and will at least give a more realistic appearance.

### 3.4.2.2 Modelling of a Surf Zone

Seaway simulation in situations when an ACV approaches a beach requires a somewhat more sophisticated model. Basically two phenomena are important to this phase of simulation:

  a. Refraction of the multi-directional wave system so that wave crests tend to become parallel to the shoreline as the beach is approached.

  b. Steepening and shortening of the waves and the corresponding decrease in phase velocity, as the beach is approached. (In the limit, phase velocity and group velocity are equal.)

It must be remembered that the object is not an oceanographic study of wave dynamics but a simple, short computer model of the surface. Both important phenomena above are basically representable by the tendency of the phase velocity of a wave to approach $\sqrt{gh}$ locally as the water depth, h, decreases to below half a wavelength. A rough but probably sufficient model for cresting and steepening is again that the velocity approaches $\sqrt{gh}$ so that the top of the wave moves faster than the bottom. As the wave front approaches the vertical, the wave breaks (or the water above the vertical point falls off).

This is admittedly a crude model of the surf dynamics involved but allows a simulation of the effect of depth on the water surface shape that is consistent with our discrete-frequency real-time model of the deep water sea and allows the wave system affecting the craft to be followed into the beach.

### 3.4.3 Aerodynamic Excitation

Wind excitation of the craft at various orientations to the wind direction has been investigated by the design contractors. (Bell Report 2.2-5 and Aerojet Report Appendix 3-6 and Section 3.2.6).

There is some question about the derivation of aerodynamic excitation from Froude scaling model tests. It is true that the superstructure of

this craft is rather blunt, and wide regions of separated flow are likely. However, there is the possibility that at the high Reynolds number of the full scale vehicle the flow will remain attached and turbulent over a significantly greater area of the craft. For this region validating high speed wind tunnel tests are recommended for aerodynamic force measurement. Above and beyond the steady open water wind excitation, there is a particular problem when the ACV is operating in the near vicinity of a larger ship. Here the effect of the turbulent wind wake of the large ship may affect delicate low speed maneuvering. For this reason, it is highly recommended that wind tunnel tests be made at the highest possible speed to determine the wind wake around a representative mother ship at various angles to the stream axis. If, for instance, the ACV is maneuvering alongside from astern on the leeward side of the mother ship and the air flow separation around the mother ship is extensive and sudden, changes in side force will result which should be included as accurately as possible in the simulation. The only way to obtain these effects is by model testing for a realistic wake model.

### 3.4.4 Aerodynamic Effector Model

The forces exerted by thrusters and control surfaces have been derived and tested at length by the AALC contractors in the course of their design procedure. Forces and moments exerted by the effectors, and in one case rudders, are described as functions of rpm, pitch, relative wind velocity and direction. The models for propulsion and control machinery described by the building contractors (Aerojet Report 3.2.6 and Bell Report 2.2.2.7) are detailed and presumed correct. MIT suggests that these models are more than adequate for the proposed ACV simulation and that they be used as is.

### 3.5    Coefficient Derivation

### 3.5.1    Analytical Considerations

The term coefficient implies that a differential equation of some order exists with something like constant coefficients to describe the motions of the craft. In usual vehicle motion studies it is assumed that these equations are second order with constant coefficients, the highest term being a force proportional to acceleration. In ship motions studies it has become usual to use this formulation but to allow the coefficients of acceleration and velocity to be frequency dependent. It is perhaps worth a slight digression

to point out one way of looking at what one is doing by introducing frequency dependent coefficients. If the displacement of a body in a direction is represented by

$$x = A \sin \omega t$$

then

$$\dot{x} = A \omega \cos \omega t$$

$$\ddot{x} = -A \omega^2 \sin \omega t$$

$$\dddot{x} = -A \omega^3 \cos \omega t$$

$$\vdots$$

If there is a restoring force, presumably hydrodynamic and having to do with the history of the free surface, proportional to the third time derivative of the displacement, then for the equation of motion in the x direction the following representation might be used:

$$m\ddot{x} = C_1 + C_2\dot{x} + C_3\ddot{x} + C_4\dddot{x} \ldots + F \sin(\omega t - y)$$

where F is an excitation force. Then.

$$m\left[-\omega^2 \sin \omega t\right] = C_1 \sin \omega t + C_2 \cos \omega t - C_3 \omega^2 \sin t - C_4 \omega^3 \cos \omega t + F$$

or

$$(m - C_3)\ddot{x} = C_1 x + (C_2 - C_4 \omega^2)\dot{x} + F$$

where F is assumed sinusoidal.

In other words for sinusoidal motion or periodic motion which may be split into discrete frequencies, the dependence of force on jerk[*] or the time derivative of acceleration may be expressed by a frequency dependent damping coefficient, the argument may be extended to all higher time derivatives. Further the inclusion of higher time derivatives is equivalent

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[*] "Jerk" means acceleration derivative.

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to describing the position as a function of past history if it is continuous:

$$X_t = X_{t-\tau} + \dot{X}_{t-\tau}(t-\tau) + \ddot{X}_{t-\tau}\frac{(t-\tau)^2}{2} + \frac{\ddot{X}_{t-\tau}}{6}(t-\tau)^3 \ldots$$

$$= F\left\{x(t-\tau), x(t-2\tau), x(t-3\tau)\ldots\right\}$$

Thus it has been heuristically shown that the inclusion of frequency dependent coefficients is therefore in a sense equivalent to introducing history dependence for sinusoidal motion. The mathematics exists for using this type of representation for study of aperiodic motions, such as maneuvering, but as discussed earlier under restoring forces, is not recommended. In traditional ship maneuvering analysis the equations are assumed to be second order and independent of frequency, in other words a low frequency limit is assumed where the highest order time dependent force is assumed to be constant "added mass coefficient" times the acceleration. It has not been determined to what extent this assumption is valid for fast maneuvering ACV's. The paper by Doctors and Sharma is certainly an indication that trouble is on the horizon. Nevertheless both for the purpose of at least getting a first approximation to the motions, for straightforward correlation with model tests, and for checkout of the anticipated more sophisticated time domain convolutionn integral technique, it is recommended that this path be followed. Equations of this type have been used by both contractors to predict maneuvering and motions of the craft. It is recommended that these equations be expressed in the time rather than frequency domain so that nonlinear (velocity squared) effects such as skirt drag may be included straightforwardly. It is not clear that added mass and wave damping terms have been investigated deeply in the contractor's simulation work. These terms may be found by extending the work of Murthy. This discussion applies particularly to terms such as side force during sideslip or "keel effect" and to pitch resonance conditions.

Simultaneously it is highly recommended that work on a convolution integral hydrodynamic model be initiated. The groundwork exists in the works of Doctors and Sharma, but must be extended to other degrees of freedom and asymmetrical cases.

### 3.5.2 Experimental Derivation of Coefficients

The preceding analytical work suggestions are in need of extensive model test verification before any confidence may be placed in the simulation. Not only the coefficients of the equations of motion, but also the motions due to transient effects must be investigated. Moreover, not only for the hydrodynamic modelling, but also for the modelling of the vehicle itself, an experimental study must be made to determine the pressure distribution characteristics of the cushion as a function of local skirt gap, fan rpm, and skirt condition. Unfortunately the aerodynamic features do not scale with Froude number but with Reynolds number, so the scale speeds should be much higher for the cushion characteristics tests than for wave force testing. It can only be hoped that the cushion aerodynamics are mainly pressure-momentum rather than viscous in nature, as suggested b. the manufacturers, so that low speed testing is valid.

The standard Naval Architecture maneuvering tests should be made with rotating arm and planar motions mechanisms to substantiate results for mean or frequency independent coefficients in the equations of motion. These tests should be made not only at nearly straight ahead but also at large yaw angles because of the ACV's ability to operate at large sideslip angles. Furthermore, four types of straight ahead seaway tests should be made:

1. Re. :oring force measurements, namely the model held steady and moved forward at constant velocity, the model forced to pitch, and the model forced to heave all in calm water at various velocities to determine restoring force coefficients of the equations of motion.

2. Exciting force measurements, namely the model held steady and the forces measured on it at various wavelengths, amplitudes, and frequencies of encounter (obtained by moving the model ahead at constant velocity). This will verify the exciting force calculations and give the limits of linear modelling of exciting forces.

3. The model should be allowed to move freely in heave and pitch into the sea to establish the reliability of seaway motions calculations. An "inverse problem" technique can be used to correlate the coefficents with non-captive model test data. (See Appendix C.)

4. The model should be accelerated with various velocity patterns as if the operator were maneuvering with much use of speed control. The drag force record with model inertial terms subtracted out will establish the validity limits of the basic amnesic second order differential equation model for wave forces.

### 3.5.3 Coefficient Extraction from Empirical Data

A great deal of mathematical analysis and experimental data has been reported by the contractors, Bell Aerospace and Aerojet General, in their Preliminary Design Summary Reports. It must be borne in mind that this information gathered during the design process and not specifically intended for a complete dynamic simulation. However, their work on thruster aerodynamics, forces, and moments, as well as on cushion and skirt aerodynamics and dynamics is not likely to be greatly improved upon by a simulation contractor. Whoever does do the simulation work should be in close contact with personnel at Bell and Aerojet for modifications and extensions of their work.

The hydrodynamic mathematical modelling done by the contractors for design predicitions, however, needs considerable development for the simulation effort, particularly in regard to unsteady or transient wave hydrodynamic effects. This problem has been discussed at length above. The use of "inverse problem" techniques should be considered.

### 3.6 Recommended Procedure for Deriving and Implementing an ACV Simulation Model

T1is section is included to provide a guidebook for an ACV simulation contractor. It is a compilation of what MIT would do if it were asked to design and program a mathematical simulator for the ACV and its intended environment. It is anticipated that the synthesis proposed here may not be unique, but at least the simulation contractor will have a place to start and a route to follow.

> Step 1 :  There is an enormous body of literature on simulation, ACV motions, maneuvering, control and equations of motion, and particularly on the hydrodynamics of pressure distribution travelling over a free surface which is the heart of this problem. It is suggested that the eventual contractor start with the partial simulation model description reported by the contractors in their Preliminary Design Summary Reports.
> Specifically, he should begin with:
>
> a. Aerojet-General, Preliminary Design Summary Report, Appendices to Volume 2, Appendix 3-1 to 3-7. The value of 3-3 is to the simulation having to do with range and endurance.

b.  Bell Aerospace, Preliminary Design Summary
    Report, Volume III, 2.2 in its entirety and
    particularly the Appendix to paragraph 2.2.2 on
    the Bell maneuvering and control simulation.

In both cases the mathematical models need further
elaboration particularly with respect to hydrodynamics
but the basic structure of the modelling is included and
the basis for aerodynamic effects, restoring forces due
to cushion immersion, and frictional drag are there.

For elaboration of the wave hydrodynamic effects the
following two references are recommended, not
necessarily because they are the ultimate law but be-
cause they are recent and include good evaluations of
the state-of-the-art and present clearly two alternative
general approaches to the problem.

a.  Doctors and Sharma, "The Wave Resistance of an
    Air Cushion Vehicle in Accelerated Motion.",
    University of Michigan Naval Architecture and
    Marine Engineering Report No. 099, December 1970.
    This report analyzes the wave drag on an ACV pres-
    sure distribution using a velocity potential - convo-
    lution integral technique for the surface profile. It
    indicates the shortcomings of amnesic modelling
    and is a good starting point for a time history depen-
    dent mathematical modelling.

b.  T.K.S. Murthy, "A Linearized Potential Flow Theory
    for the Motions of an Air Cushion Vehicle in a Seaway",
    von Karman Institute for Fluid Dynamics Lecture
    Series 33, February 1971. This paper develops the
    surface description and resulting forces and moments
    using an acceleration potential technique for steady
    motion and sinusoidal inputs. It makes no attempt
    to treat transient effects. However, it is a good
    starting point for traditional motions analysis. It is
    a perturbation expansion based method with higher
    order terms dropped. The extension of the expansion
    to higher order is possible if tedious. The output of
    this approach has the advantage of correlation with
    planar motion or rotating arms tests and traditional
    phraseology such as added mass and damping.

Step 2 :  MIT's recommendation is that both types of approach to
          free surface mathematical modelling should be followed
          up. The amnesic modelling is obviously not the ultimate
          answer, but is straightforward and the analytical develop-
          ment needed is small so that a system could be "on-line"

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in a minimum time. The first thing we would do is to put
a programmer and an engineer on developing the steady
and sinusoidal input for computer use with six degrees of
freedom and the types of pressure distribution expected
beneath the Bell and Aerojet crafts. Simultaneosuly work
should be initiated on the development of the convolution
integral approach. This approach has the advantage of
being basically temporal and being able to represent the
wave forces on the vehicle as a function of time during
quick maneuvers but does require more analytical de-
velopment and programming to keep computer time down
One would then be tempted to try an acceleration potential
description as described by Murthy but in the time history
framework as described by Doctors and Sharma since
acceleration potential seems a more direct approach to the
problem with pressure boundary conditions rather than
velocity potential.

Step 3 : Immediate tests should be initiated on the pressure dis.ri-
bution under the craft models with various skirt clear-
ances. MIT believes these tests to be simple, requiring
only a table with manometers of other pressure gauges.
However, the hydrodynamic modelling is dependent on
the detailed pressure distribution and the best possible
data should be at hand as soon as possible.

Step 4 : Initiate model testing for maneuvering and seakeeping.
Especially, data on drag while accelerating should be
obtained.

Step 5 : Use the contractor's data on skirt drag, fan and thruster
characteristics and initially on external aerodynamics.

Step 6 : Do wind tunnel testing at the highest possible speed for
the external aerodynamic forces and moments on the
craft at various angles of attack. Also obtain wake data
on a representative mother ship at various angles of
attack.

Step 7 : Program a realistic seaway, long crested at first. Make provision for steepening and sloping in shallow water.

Step 8 : Compile data and program software for eventual simulator use.

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## CHAPTER 3

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3.  Mandel, Philip, Ship Maneuvering and Control, Chapter 8 of Principles of Naval Architecture, published by the Society of Naval Architects and Naval Engineers.

4.  Bell Aerospace Corporation, "AALC Preliminary Design Summary Report", Volumes I through IV, October 1970, Navy Contract N00024-70-C 0267.

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# CHAPTER 4

## MAN-IN-THE-LOOP SIMULATION
## REQUIREMENTS FOR ACV'S

### 4.1 Summary and Conclusion of Chapter

This chapter is addressed to the man-in-the-loop aspect of the ACV simulation. First, the importance and necessity of explicit simulation of man-machine interfaces is discussed in the light of the various scenerios in which an ACV must maneuver in proximity to obstacles, to other ships, or to where a surf zone must be negotiated. Visual and kinesthetic requirements are itemized and a heave-only kinesthetic simulation is proposed. The state-of-the-art in scene generation and displays is reviewed. It is concluded that the traditional and most common technique for visual simulation, i.e., the scale model and camera approach, has very definite limitations and inherent disadvantages including physical size, awkwardness of electro-mechanical systems, no growth potential and high cost. In contrast, the computer assisted, electronic scene generation approach offers significantly greater capability and flexibility without the inherent physical and electro-mechanical drawbacks of the model and camera approach. Recently, this approach has been developed to the point where it can now be used to generate very realistic scenes with a cost which appears to be competitive with the model and camera approach. It is now estimated by MIT that the new technology has progressed sufficiently to give serious consideration for use in the ACV simulation problem. In view of the AALC program needs and in consideration of the fast evolving state-of-the-art, a computer assisted, electronic scene generation is recommended, together with a panoramic projection system. Potential applications to other Navy programs are suggested. The option of implementing the kinesthetic effects at some later point in the AALC program, after completion and operation with the visual simulation only, is also discussed. Cost estimates and an acquisition plan are given in Appendix A.

## 4.2 Necessity of Man-In-The-Loop Simulation

The incorporation of an operator and the associated manual inputs to the basic ACV control simulation, along with the corresponding visual and kinesthetic feedback signals to the operator, provides a significantly enhanced evaluation capability. Indeed there are certain facets of the ACV control problem which cannot be satisfactorily evaluated without an explicit and realistc man-machine interface. Because of the uniqueness of the ACV control problem for an operator with respect to conventional crafts, because of the docking requirement at a fair accuracy to a moving target, and in view of the potential ACV habitability problem in heavy seaways and high speeds, it is obvious that a simulation capability which does not include the man-in-the-loop at some time can at best provide only part of the answer to the $AC^V$ control problem. Furthermore, in order to successfully study and strive at the important goal of obtaining a craft operable by personnel other than highly trained technical operators, the man-in-the-loop portion of an ACV simulation becomes mandatory and will be useful to assess early the impact of crew skill level on cockpit equipment design. Of particular significance is the availability of a number of control options in various combinations permitting maneuvering the ACV by many different manual procedures. Two questions arise: first, how much automatic control is desirable to augment the craft stability and maneuverability by a lesser-skilled operator; and, second, which manual procedures are to be retained and recommended among the many possible ones, with due consideration given to safety, consistency and future training requirements. Each manual procedure, with or without automatic controls such as yaw rate damping, is characterized by its own time constants; for instance the manual procedures and time constants involved in yawing the ACV depend on whether the forward thrusters, or forward-pylon-supported propellers rather than the rudder or rear-pylon-supported propellers are used. It is felt that for the sake of safety, efficiency, and expediency in crew training these questions must be studied on a man-in-the-loop simulator. Finally, an additional consideration for the man-in-the-loop simulator is that it can be the forerunner of a Naval Training Device.

## 4.3   Man-In-The-Loop Simulation Equipment for ACV's

In order to provide the ACV simulation facility with the necessary visual and kinesthetic effects, there are three basic requirements:

1) A mock-up of the operator's cabin with the various controls and indicators — the internal environment.

2) The generation of motion of the cabin to simulate the significant kinesthetic inputs to the operator.

3) The visual presentation of the simulated external environment.

Among these, 1) is the easiest to implement, while 3) is the most difficult and costly, but also the most necessary requirement. It is felt that the kinesthetic simulator implementation has a lower priority than the implementation of the visual simulator.

It was found that the manned simulator problems for the ACV are similar to those of simulators for conventional ships, aircrafts and spacecrafts. A study of the ACV requirements, of representative configurations of other simulators, and of the available technology has led to a set of recommendations for each of the above requirements.

## 4.4   ACV Cabin Mock-up Requirements

In order to provide for a simulation facility which will permit the maximum possible control evaluation, the cabin mock-up should contain as many of the control and visibility features as possible which are in the actual cabin environment. Mock-ups should thus be constructed of each of the vendor's control cabins, taking particular care to provide as realistic an appearance as possible. Since the cabins will obviously never see actual wind loads or sheets of spray, they should be made much lighter than actual cabins to minimize loads on the kinesthetic motion platform. Following the present practice in the aircraft industry, the entire control cabin should be removable as a unit from the simulator platform. Connections for control outputs and inputs should be made interchangeable, and both mock-ups should be designed to use the same visual display system.

## 4.5    Kinesthetic Simulation Requirements

### 4.5.1    Desirability of Kinesthetic Simulation

One of the most important questions which the simulator can be used to
evaluate is that of controllability and habitability under the kinesthetic
influences which will be experienced by the operator.   These influences
impact the mission capability of the craft as much as maneuverability or
any other criterion which can be evaluated by the simulator.   Of particular
importance is the visual-kinesthetic simulation to the pilot when the ACV
is negotiating surf.   The concept of "surf-riding" by an ACV must be
researched on a simulator that not only renders the force and moment
inputs to the craft but also the kinesthetic acceleration in the pilot whose
task it is to watch the surf, "catch" the wave, maintain a safe yaw attitude,
match the craft speed with surf speed and properly conduct the beach landing
operation.

### 4.5.2    Analysis of Axes for Motion Simulation

In analyzing the axes in which motion should be simulated kinesthetically,
it is clear that heave motion of the craft is the most important.   Craft
pitch and roll are important only to the extent that they produce heave
motion at the operator's station.   It is felt that because the craft pitch
and roll angles are nominally small, at least for operation over water,
the kinesthetic inputs to the operator from these motions would be small
if simulated.   Experience on a ship when it is rolling and pitching with
similar amplitude indicates that when one is seated near the center of
the ship it is virtually impossible to make a seat-of-the-pants judgement
about the ship's attitude without reference to the horizon.   An experience
probably familiar to many is to have glanced casually out of the port hole
of a ship's stateroom or dining hall and have observed that the apparent
large up and down motion of the horizon seemed quite divorced from the
small sensation of motion experienced inside the ship.   Another reason
why the craft pitch and roll motions should not be kinesthetically simulated
is that they are not directly related to control motions by the operator of
the craft, unlike an aircraft where pitch and roll sensations provide
kinesthetic feedback.   At best, pitch and roll rates on an ACV would be
disturbance inputs only; and since the disturbances are small, they may
be neglected.

The other motions, surge, sway and yaw, should be even less important as kinesthetic inputs than pitch and roll. The lateral and angular accelerations should be quite small except in a plow-in situation, and when this happens the craft cannot be controlled anyway.

Even though the proposed simulator would have only kinesthetic motion in one degree of freedom, heave, the other five motions would, of course, be simulated visually and, where applicable, in the displayed instrumentation. Since in the real world the operator perceives the motion about these five axes primarily be means other than kinesthetics, this should be quite satisfactory.

### 4.5.3 Implemenation of a Heave Kinesthetic Simulator

In order to implement the heave motion of the simulator platform, it is recommended that from the standpoint of both performance and system cost a hydraulic servo system be utilized. It should be designed to have a maximum travel of ±3 feet with a peak acceleration of ±3 g's. It is estimated the total weight of the platform would be approximately 1500 lbs, so that the requirements on the motion system would not be particularly severe. There are obvious implications on the visual display system created by the heave motion of the simulator platform. These will be covered in the following sections. (Functional overlapping between kinesthetic and visual simulators, see 4.8.3.)

An option which could also be considered here would be to initially implement the cabin mock-up and visual presentation only so that the man-in-the-loop simulation could be conducted without the kinesthetic inputs. Implementation of these two areas could be designed and planned in such a manner that the subsequent addition of the motion platform could be accomplished with negligible impact. Such an approach would still permit valuable simulation testing while providing more of a time-phased procurement.

### 4.6 Visual Simulation Requirements for ACV's

For systems such as fleet submarines and deep submersibles where the display problem consists of dial reading and CRT viewing, the dynamic and cockpit simulation can be achieved through relatively straightforward approaches. In systems where direct through-the-window viewing must be simulated, such as ACV's, the problem becomes much more difficult. In

the first case, dial readouts and only rather abstract sonar patterns are required. Direct scene viewing immediately implies images of significantly greater complexity. In the ACV simulation the required display consists of both ocean and terrain scenes, with the content including waves, surf, ships (LSD and other ACV's) and various ocean and terrain obstacles. It is also required that both motion of the viewing point, with the corresponding changes in scene perspective, as well as the motion of objects within the scene, such as an LSD, be produced in the visual display.

The first requirement of the visual presentation, then, is that it provide a dynamic, real-time display of the simulated environment. Second, it must look as much like the actual environment as possible, and contain a prescribed repertoire of scenes. Third, the field of view must be sufficient to provide the operator the comparable visual cues which would be present in the actual operation of the craft. For the ACV simulation it is considered essential that a very wide field of view on the order of at least 170° be provided for the following reasons:

    a. For both the alongside maneuvering situation and the crossing of surf, the operator needs to look to the sides as well as ahead.

    b. In maneuvers, the ACV can easily be moving in a direction 45° to the fore-aft axis.

    c. The pilot senses velocity by peripheral vision of the angular rate of the texture of the moving surface beneath the ACV.

## 4.6.1 Repertoire of Visual Scenes to be Generated

The specific scenes which should be generated should achieve the following:

    1. <u>Over Terrain</u> — Terrain should include hills or slopes, ditches, obstacles such as houses, walls, step changes in elevation, and trees. Beyond these features a flat terrain extending to the horizon is desirable. These terrain features may be all located within an area 1 mile by 1 mile.

    2. <u>Beach</u> — The beach scene is composed of surf, a smooth sloping beach, trees or other objects at the upper edge of the beach, and a flat terrain beyond the beach. The line of the crests of the breakers is parallel to the beach; the

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crests will have variable spacing. In its simplest form the
surf may be stylized to be only a flat, textured, moving
surface. This scene will be viewed both in going from the
ocean to land and returning.

3. <u>Ocean with Obstacles</u> — The ocean would consist of long
   crested waves extending to infinity in all directions. The
   crests would be uniformly spaced and move at a constant
   velocity. In its simplest form the ocean may also be
   stylized to be only a flat textured surface that moves with
   respect to the stationary objects. The interaction of the
   waves with the ships' hulls represents an aspect of the
   display problem of varying difficulty, depending upon the
   method used in the visual display. This will be covered
   in the discussion of the visual display options. Also in-
   cluded in the ocean scene would be several stationary box-
   like obstacles. These would represent objects the ACV
   may have to avoid.

4. <u>Ocean with a Supply Ship</u> — The supply ship may move at
   low velocity over the ocean surface at any heading with
   respect to the waves. In addition to being free in azimuth,
   the ship may be subjected to heave, pitch and roll motions;
   these motions will be apparent with respect to the ocean
   surface.

5. <u>Ocean with an LSD</u> — Included as a part of the LSD should
   be an entrance well in the transom for the ACV. As with
   the supply ship it is free in azimuth , it can move with
   some velocity over the ocean surface and it may experience
   heave, pitch and roll motions which change the ship's at-
   titude noticeably with respect to the ocean surface.

6. <u>The Visual Simulation of Fog</u> — The option should be
   provided for making the visual scene contrast a function
   of the range along the line of sight. Ideally, this would
   be accomplished by summing an intensity signal pro-
   portional to range with the scene information.

## 4.7    ACV Cockpit Scene Generation

With the given requirements for the scenes to be simulated the remaining consideration is the actual generation of the visual presentation. The task of providing the operator with the dynamic, real time visual display of the ACV's operating environment involves three primary tasks. The first requirement is an initial static image of the environment (image storage), the second is a capability of imparting dynamic motion to this image, and the third is the requirement of a display device for presenting the resulting image to the operator. The method utilized for providing the image storage will dictate the options available for the second requirement — that of animation of the image. Both of these, in turn, will determine what options can be considered in selecting the display device.

### 4.7.1    Image Storage and Animation Systems

Various techniques have been used in generating the initial scene image. Traditionally the most predominant of these has been the use of a 3-dimensional model of the operating environment with either optical or TV viewing. Other techniques have utilized photographic film in the form of pre-recorded motion pictures or photographic transparencies. The most recent development is in the area of computer assisted, electronic scene generation techniques.

### A.    Image Storage by 3-D Scale Models

Inherent in the first approach utilizing a model is a highly realistic scene representation, both in detail and in perspective, which is limited only by the skill of the craftsmen. As always, there are disadvantages with this technique. These include physical size, both of the model and of the gantry required for the camera probe, complexity of the electro-mechanical systems required for providing the camera probe with the necessary mobility, the high illumination levels required, susceptibility of the model to damage by the camera probe, and the difficulty of providing motion within the scene. This latter disadvantage is particularly significant in this application where motion of other ships within the scene is required as well as wave and surf motion. Hybrid approaches can be used with video insertion techniques so that wave motion, for example, can be generated separately [2], but this further increases system complexity. Also, since both water and terrain scenes are required, two separate

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models must be constructed and located within the simulation facility. Another limitation of this technique is achieving sufficient field of view while retaining depth-of-field, resolution, minimum distortion, sufficient light gathering ability, and the capability of achieving close proximity to the model. In order to achieve a field of view in excess of the $90^{\circ}$ - $100^{\circ}$ of conventional wide angle lenses, various techniques have been employed, but each of these also has limitations. Farrand Optical Company has a $140^{\circ}$ probe utilizing the "Scheimpflug" principle which permits focusing over the entire field of view on a two-dimensional plane, but objects above this plane such as the LSD and vertical obstacles are out of focus[6]. Additionally, the $140^{\circ}$ F.O.V. places stringent resolution requirements on the TV camera. Techniques of splitting the image through the use of prisms into three channels have been used, but edge-to-edge registration is a problem and complexity is again increased. In summary, although realistic scene generation can be accomplished with this technique, there are significant limitations and costs inherent in this approach.

## B. Other Image Storage and Animation Devices

The other approaches utilizing film techniques deserve mention, although due to their basic limitations it will be obvious that they are not applicable to the ACV requirement.

One example of the use of pre-recorded motion picture film is the fire-control simulators for Army tank trainers. Although a variety of maneuvers of the enemy tank can be simulated, it is completely pre-programmed with no provision for interactive maneuvering of the viewing point. This is realistic for this type of simulator, however, since the firing point is fixed for a given shot.

In order to provide less of a pre-programmed effect, transparencies have been used in several different techniques to provide for a variable perspective which changes as a function of movement of the viewing point. For example, if one were simulating a landing on an aircraft carrier the runway would ideally change from a small rectangular strip when viewed at a distance to an increasingly larger "key-stoned" shape as it is approached. This change in perspective is achieved in the point light source system by projecting a bright point light source through a transparency and then moving one with respect to the other. In the flying spot scanner system a transparency is placed against the

face of the flying spot scanner which scans the image with a raster
pattern controlled to generate the correct perspective and motion of
the scene. By changing the shape, size and angular orientation of
the scanning pattern, complete freedom of motion within the image
area is possible. Since these techniques are essentially limited to
two-dimensional images, they are more suited for applications such
as aircraft simulators, but completely unacceptable where simulation
of surface maneuvering in the vicinity of three-dimensional objects
is required as in an ACV simulation. The possibility does exist that
the flying spot scanner approach could be used to generate the waves
for a hybrid system utilizing a model with video insertion techniques,
but not without the cost of considerable additional complexity.

C. Electronic Image Storage and Orientation

The most recent development in scene generation techniques is the
use of computer assisted, electronically generated displays. Here
the surfaces of the simulated scenes are represented by basic poly-
gonal shapes with the locations and lengths of the edges being stored
digitally along with the reflectance and hues (in color systems) of the
enclosed surfaces. A special purpose processor then operates on
this data to produce a video display on a monochrome or color cathode
ray tube or TV projector. Generation of the scene is accomplished
at a rate of 30 times per second consistent with conventional television
display rates and at each cycle the perspective of the scene is computed
as a function of the simulated location and orientation of the operator's
control station. With the processing speeds available with this tech-
nique, motion of the viewing point produced by simulated maneuvering
of the observer's vehicle and motion within the scene of moving crafts,
etc., are immediately reflected in changes in the scene perspective.
(See Figure 4-1.)

The assistance of a computer, referred to as the "host computer", is
variable but may include the following: initial storage of mathematical
picture definition; calculation of motion within the scene and proper
parametric update; calculation of motion and direction of viewing point,
etc. Clearly, storage and low frequency tasks can be ascribed to the
host computer, while the high speed algorithms, occultation definitions,
video refreshing, etc., are ascribed to the special purpose processor
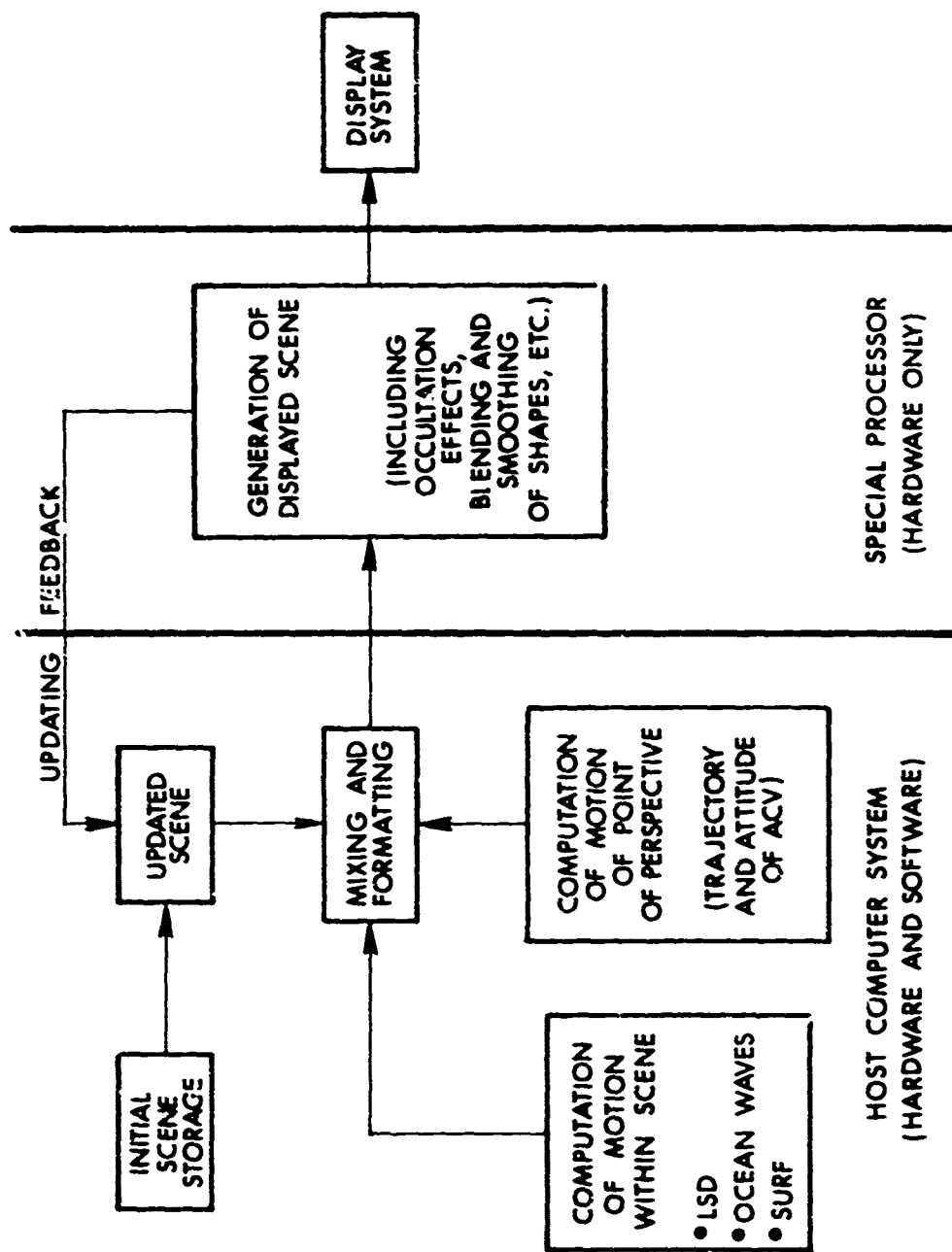and interface devices.

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Figure 4-1 Configuration of an Electronic Scene Generation System

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A real-time display can thus be produced with complete freedom of movement both within the scene and from the observer's viewing point. The resulting display is strikingly realistic. The most recent algorithms permit the visual presentation of objects with smoothed edges and modulated shades of grey and color. The digitization or quantitification of the object and scene definition is not apparent and the net result would appear as "realistic" as what any electro-optical scale model mock-up approach could do if one considers the substantial optical losses of the latter from the wide angle pick-up lenses to the wide angle projection lenses. The image detail of the electronically generated scene is limited only by the number of edges which can be stored a. processed during the iteration cycle. The present state-of-the-art offered by the most recently developed algorithms permit approximately 3,000 "edges" in the displayed portion of a scene (there can be more than 3,000 edges if one includes edges that are "hidden" or occulted for the given location of the point of perspective)[*]. It is felt that 3,000 edges is more than adequate for the ACV simulation application.

The immediate advantages of an electronic, computer-assisted scene generation approach are:

    a.  Extreme flexibility in scene type and content, ease of change of scene material.

    b.  Flexibility in generation of motion within the scene and of the point of perspective.

    c.  No large model and gantry configurations.

    d.  Essentially no electro-mechanical components, thereby minimizing setup and maintenance requirements.

    e.  No high brightness illumination requirement.

    f.  No depth-of-field problems — entire image continuously in focus.

    g.  No requirement for protection of a scale model against damage by the camera probe.

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[*] Edges here are defined as the sides of each of the polygons representing object surfaces. In the case of adjacent polygons where there are common sides, the sides are counted for each polygon.

### 4.7.2 Scene Display Systems

Just as in the case of the scene generation problem, various techniques have been used to produce the visual display of the simulated scene. Of these, there are three major types — direct CRT viewing, infinity imaging systems, and projection systems. The limitation on direct CRT viewing is immediately obvious if any appreciable field of view is required. (If the actual operator's station utilizes a CRT as the primary visual display, however, this technique is ideal, but that is not the case for ACV cockpits.)

### A. Infinity Imaging Systems

In the infinity imaging systems, either refractive or reflective viewing optics are utilized to provide a relatively wide field of view of a virtual image of the input image source which is normally a CRT. The image displayed by the CRT can either be generated from a model and TV camera source, generated by electronic means, or generated by hybrid techniques. The virtual image is focues at infinity, which is generally valid for through-the-window viewing situations, and produces a realistic stero-like effect with proper motion parallax. It can also be made to be relatively compact, particularly in the case of the "pancake window" type, so that it can be mounted as a part of the operator's cabin on the motion platform. This is not as essential in this application, since motion would be produced in the heave translational axis only and not in any of the rotational axes. The optics for these systems can take several forms. In the refractive system, the eyepiece is a large, usually plastic lens up to 6 feet in diameter. Good optical correction is one of the major problems with this approach. Reflective systems give better optical correction and are generally superior to the refractive systems, although because of the large beam splitter elements they are somewhat more susceptible to vibration. The third, or "pancake window" type, utilizes an in-line reflective system employing special polarizers, a quarter-wave plate, and a beam splitting mirror in a layered, shallow unit (hence, the name) in front of a special spherical-faceplate CRT. The virtual image of the CRT image is again focused at infinity, and is said to produce a very realistic display. It is much more compact than the other two systems; however, the optical transmission is lower (nominally 1%)[7], and is relatively costly where a display of moderate size is desired.

In order to achieve the wide panoramic view required to simulate the ACV cabin, the configuration which would be used with the infinity imaging systems would be to place three of these systems side-by-side in a wrap-around arrangement, with approximately a $150^{\circ}$ horizontal by $35^{\circ}$ vertical field of view being reasonably achievable.

B. Projection Systems

In the projection system, as the name implies, the operator views an image projected onto a panoramic viewing screen simulating the field of view of the operator. For operation with video systems, any of several television projectors can be used including General Electric's light valve projector, the Eidophor projector, or the Display Sciences' projection CRT. The first two utilize a deformable oil film, Schlieren optics and light source to produce a projected image corresponding to the pattern "written" into the oil film by an electron beam modulated with the video input signal. The projection CRT's utilize a high intensity CRT and high efficiency reflective (Schmidt) optics to project the CRT image onto the display screen. Each of these types is commonly used in both monochrome and color auditorium television displays and produce good quality images with good brightness levels. Of the two basic types, the light-valve type appears to give somewhat superior performance to the projection CRT type.

Either front or rear projection systems can be used with either single or multiple projector configurations. Five possible configurations are indicated in Table 4-1 and Figures 4-2 through 4-6, with the advantages and disadvantages being listed for each.

Even a cursory examination of the alternatives listed indicates that the best approach is number 3 where three commercially available projectors are used. The use of three projectors actually has advantages of better resolution and higher intensity output than could be obtained from one conventional projector if such a projector could somehow be made to fill a wide screen. The fact that the screen cannot be made a uniformly curved arc should not detract significantly from the visual display. Although fairly narrow angle Schmidt or mirror type projectors are best for CRT projection systems where the largest possible effective aperature is required, a wide angle refractive projection system does exist with substantial power output and high resolution. This is the G.E. model PJ-700 (black and white) which has

TABLE 4-1

Potential Projection Configurations for
an ACV Visual Scene Simulation

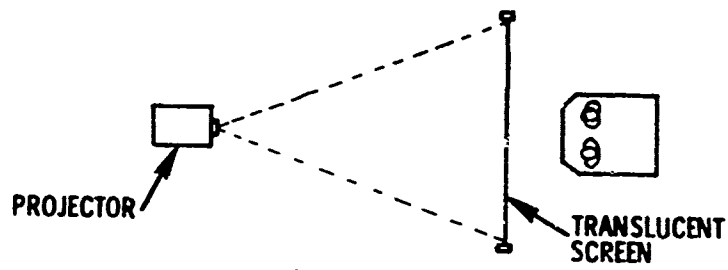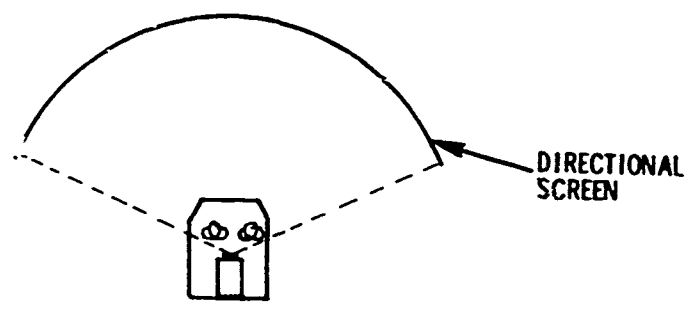| Alternatives | Advantages | Disadvantages |
|---|---|---|
| 1. Large rear screen projection, flat screen, single projector<br>(See Figure 4-2) | • Adequate observer viewing angle<br>• One projector<br>• Color or B & W | • Low overall intensity<br>• Severe loss of intensity at edges; Fresnal lens not practical<br>• Low resolution<br>• 3 x 4 display ratio<br>• Cannot heave with observer |
| 2. Wide angle front projection, 100° anamorphic lens, directional screen<br>(See Figure 4-3) | • Adequate observer viewing angle<br>• One projector<br>• Curved screen reasonable<br>• Reasonable aspect ratio 3 x 8 | • Very expensive lens design; probably small aperature<br>• Low resolution<br>• Not possible to use Schmidt projector<br>• Marginal in intensity |
| 3. Three conventional projectors, front projections, directional screen, blended screen corners<br>(See Figure 4-4) | • Very wide angle<br>• Good intensity<br>• Good resolution<br>• Good aspect ratio 3 x 12<br>• Wrap around screen<br>• Color or B & W<br>• No special develop. needed | • Screen not a uniform arc<br>• Most Schmidt projectors cannot be used because of the relatively wide projection angles required. |
| 4. Single 45° angle projection system, directed in direction of observer's head; curved screen<br>(See Figure 4-5) | • Amenable to 360° operation<br>• Good intensity<br>• Good resolution<br>• Good aspect ratio<br>• Wrap around screen | • Poor peripheral cues<br>• Apparatus required on observer's head |
| 5. Mechanically swept high intensity arc system; 180° coverage; light modulated by Kerr Cell or equivalent<br>(See Figure 4-6) | • High brightness possible<br>• Very high resolution possible<br>• 120-180° field<br>• Good aspect ratio<br>• Wrap around screen | • Mechanical sweeper very difficult to develop; 236, 250 rpm required with 4 sided mirror and 525 lines<br>• Substantial optical development required |

Figure 4-2



Figure 4-3
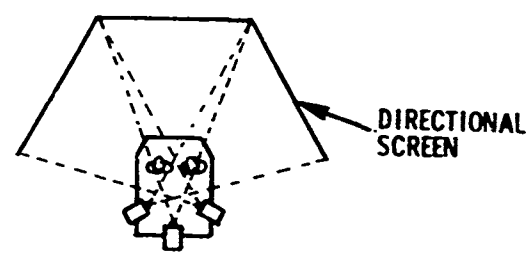


Figure 4-4

Projection Configurations

DIRECTIONAL
SCREEN

PROJECTOR SLAVED
TO OPERATORS HEAD

Figure 4-5



DIRECTIONAL
SCREEN

HIGH SPEED
SWEEPER
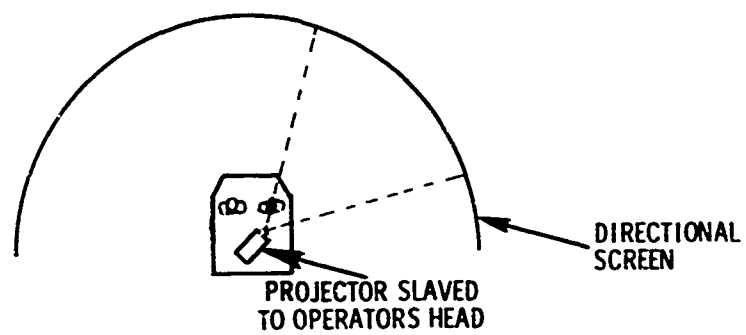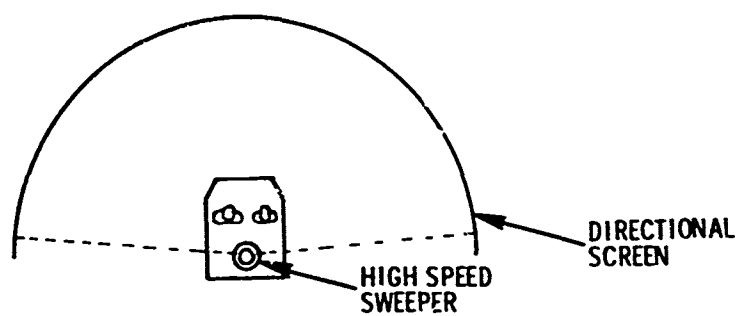
Figure 4-6

Projection Configurations

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about 800 lumens output and a ratio between projector distance to the screen (or throw) and the image width of 1.5 : 1.

Of the two potential display approaches, the projection system is considered superior to the infinity imaging system for the following reasons:

      a.   Larger obtainable image, hence larger practical field of view.

      b.   Less complexity.

      c.   Utilization of commercially available components.

      d.   Lower total cost.

4.8      <u>Selection of a Visual Scene Generation and Display System for an ACV Simulation</u>

4.8.1   Equipment Recommendation

Having reviewed the state-of-the-art in scene generation and display techniques, the configuration recommended for the ACV control and motion simulation would utilize electronic, computer assisted scene generation and a three-channel panoramic projection arrangement. For the reasons enumerated above, it is felt that the electronic scene generation technique is far superior to the model approach. In the evaluation, particular attention was paid to the requirement for the dynamic representation of the waves. It is felt that these could be modelled quite realistically with this technique through the use of the segmented polygonal surfaces with a repeating pattern of perhaps six waves of mixed amplitude and spacing being used to reduce the total computer storage requirements for the wave "field". Realistic intersections between the waves and the ships' hulls would also be directly obtainable with this technique. Each of the other required objects within the operating environments, as specified in Section 4.6, could also be represented with more than adequate realism.

Generation of the three views for the three channel projection arrangement is accomplished directly with this approach with only a moderate increase in programming. The available image detail can either be distributed evenly between the three views or concentrated more heavily in a given sector depending upon the visual scene situation. The resulting displayed scene will contain more than adequate detail, and definitely have better resolution than that obtainable with a model approach. A monochrome

system is recommended, however a color system could be considered. The primary consideration between the two would, of course, be the budge .ry aspect (see Appendix A). Modification at some later time to incorporate color would also be an available option. It is felt that the implementation of a monochrome system for the initial facility would be the preferable approach.

The choice of the projection system over the infinity imaging system was made primarily on the basis that although a completely satisfactory display would be obtained with either option, the projection system represents a somewhat simpler approach utilizing more standard, commercially available equipment. The specific configuration recommended is shown in Figure 4-7. Each of the three projected images would be approximately six feet high by eight feet wide, at a viewing distance of approximately eight feet, resulting in a combined field of view of approximately $170^{o}$ by $40^{o}$. The projectors would be monochrome, of the light valve type, although the same comments with respect to color apply here also. (See Appendix A.) There is an additional minor consideration in the color-monochrome question concerning resolution. Both systems would operate at 525 vertical lines with the horizontal resolution being 800 TV lines (per channel) for the monochrome projector and 600 TV lines for the color projector. The difference is not significant, and either would produce a good quality display. If subsequent conversion to color were desired, the monochrome projectors could be modified at the factory - procurement of new units would not be required.

4.8.2 Other Utilization of the Recommended Visual Simulation Equipment

In addition to the ACV simulation, the facility which is recommended would obviously provide a powerful simulation tool for training and evaluation with other crafts and operational situations. With only a modification being required in the programming for the specific task, the potential applications would include hydrofoils, VTOL aircraft, helicopters, displacement ship maneuvering, destroyer docking, refuelling or cargo transfer at sea, etc. Additionally, when not in use for simulation, the scene generator with three views as proposed could be used interactively for constructing new scenes to be used in the simulation or equally well for any other visual display task. For example, three separate CRT terminals could be set up in different locations for use as design tools in constructing separate 3-D visual models of ships' hullforms, aircraft designs, buildings, or structures.

FIXED
PANORAMIC
SCREEN

MOVABLE PLATFORM
ALSO CARRYING
PROJECTORS

PROJECTION
HEAD

FLEXIBLE
CONNECTIONS

FIXED

PROJECTION
CONTROL
UNITS

FRONT
PROJECTION
SCREEN

RIGHT
PROJECTION
SCREEN

PROJECTION HEAD

PROJECTION
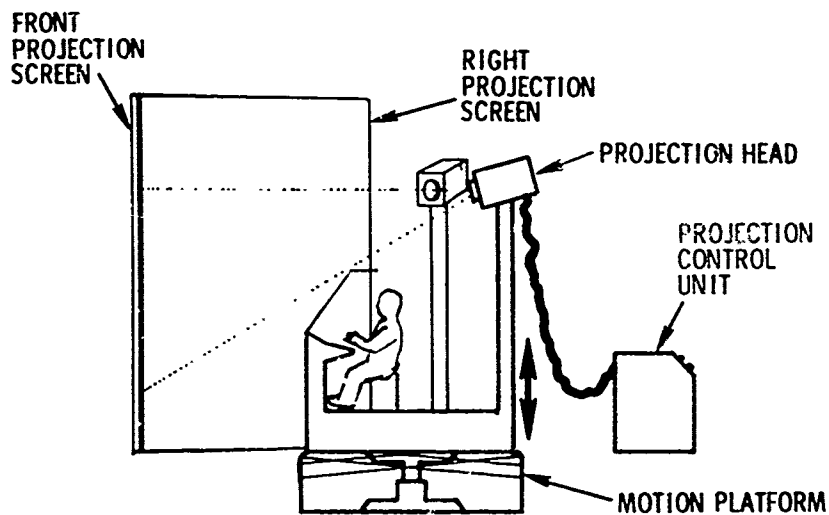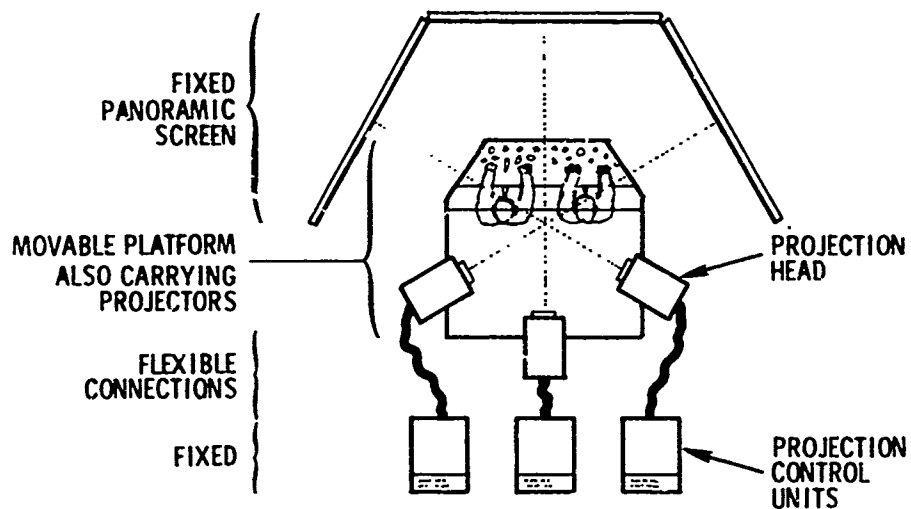CONTROL
UNIT

MOTION PLATFORM

Figure 4-7

Projection Configurations

### 4.8.3 Integration of Kinesthetic and Visual Simulation

The integration of the kinesthetic motion of the control cabin with the recommended visual simulation configuration would be accomplished as follows. The video projectors would be mounted on the motion platform and the projection screens designed with sufficient vertical height to accommodate the vertical displacement of the projected image as a result of the heave motion of the control cabin. An apparent fixed viewing angle of the projected scene would thus be provided, with the horizon in particular maintaining a constant angular position with respect to the operator. With computer assisted, electronic scene generation being used for the input image, the relative position of simulated points between the operator and the horizon can be made to shift with correspondingly less vertical travel, thus producing proper motion parallax as a function of simulated viewing range. With the PJ-700 video projectors which are recommended, the projection heads can be located remotely from the main units, thereby reducing significantly the loading on the motion platform.

### 4.8.4 Computer Requirements Specific to the Visual Simulation

The computer requirements for the visual simulation would be of two types: 1) bulk storage of scene content after processing in the scene generator, with no computational time required from the host computer, and 2) the computation of location and direction information for each of the objects within the scene with respect to the operator's vantage point. Since the vantage point will be moving in accordance with the dynamics computations for the ACV within the computer, this will result in corresponding changes in the reference data to the various objects within the scene. In addition, where there is motion of objects within the scene, this will also result in changes in the reference data.

The additional computer capacity required for the first function is approximately 26 K (32 bit word length) of core memory with multiport input/output capability for reading out at a rate of thirty times per second for display refreshing. This can either be provided through additional core in the host computer or through separate "stand-alone" memory. For the second function, namely the computation of reference data for objects within the scene, the primary factor influencing this data is the motion of the ACV itself. The real-time computation of this motion is, of course, provided for in the hybrid model within the host computer with the result being that the majority of the task is thus accounted for. The remaining computational time is such that it can be accomplished by the host computer

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with no increase in capacity.

4.8.5   Cost Estimates

The estimated costs for the above hardware based on discussions with
the various vendors involved are indicated in Appendix A.

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# CHAPTER 5

## SELECTION OF A COMPUTER SYSTEM
## FOR A NAVAL SIMULATION FACILITY

The selection of a computer system for a simulation facility with the
specific objectives of supporting developmental Navy programs is a
complicated process with multi-faceted choices and a host of factors
to consider. The real-time computation needs and the requirement
to link these computations with man-machine interfaces and other
ship, craft or boat devices dictates a non-EDP approach in computer
selection. Since overall cost-effectiveness cannot be obtained after
the fact, it must be assured by a directed exploration of require-
ments, both present and future, and by matching available industry
systems to these needs.

### 5.1    Summary and Conclusion of Chapter

This chapter summarizes the computer requirements already e lored in
previous chapters, establishes the necessity for a digital/analog hybrid
computer, emphasizes the need for growth potential and strongly suggests
that a multi-access, multi-user computer capability is necessary for
attaining overall facility cost-effectiveness. Goals and selection criteria
are itemized for both the analog and digital portions of the hybrid facility.
A thorough review of the industry offerings has been made and is sum-
marized in Appendix D. The review also includes the results of a rather
intensive canvassing of actual systems users (about 50 companies scat-
tered around the U.S. and Canada). The collection and structuring by
MIT/DL of these opinions and individual assessments will guarantee an
objective and balanced evaluation of computer candidates and minimize
the risk involved in procuring a Navy simulation facility. Final recom-
mendations are made. Three computer systems are retained as valid
candidates if one ingores the multi-access computer requirements. These
are: the SEL 8600, the XDS Sigma 8 and a yet unannounced but promising
computer, the DEC PDP-10 with KI-10 processor.

MIT's feeling, however, is that the multi-access feature is mandatory for the type of customer environment in which the Navy simulation facility will operate, especially if one considers the low cost increment that a multi-user configuration implies. If one heeds the important need for a demonstrated multi-access capability, only two computer candidates remain in consideration, the XDS Sigma 8 and the DEC PDP-10 I. Furthermore, if time-sharing is a mandatory computer feature (as opped to batch operation) in MIT's opinion a worthwhile capability in need of early consideration, the DEC PDP-10 with KI-10 processor seems to remain ahead as the most desirable computer.

Neither the XDS Sigma 8 nor the DEC PDP-10 I yet exist on the market. But it is no accident that a comprehensive and balanced study leads to a recommendation of advanced state-of-the-art systems not yet strictly available. No undue risk is caused by recommending these systems, since a) they will be put on the market by the vendors shortly; b) the reliable utility software packages developed and proved for the less advanced systems are fully upward compatible; c) there are interim computers available that can be used until the advanced computer is available, and the changeover from interim to advanced computer would involve a minimum inconvenience; and d) both vendors are experienced and reliable in their expansion and growth plans so that minimum risk is to be expected.

Appendix D gives a factual summary of data gathered during the selection study on both analog and digital computers; it also includes summaries on the three companies and their candidate system which MIT is recommending for a Naval Simulation Facility.


5.2     Necessity of a Hybrid, Digital-Analog Facility

There are three a priori computer configurations to be considered for a multi-purpose Naval Simulation Facility, oriented towards real-time motion and visual simulation:

1. An all-analog facility
2. An all-digital facility
3. A hybrid facility consisting of both an analog and digital computer.

It will be briefly shown that all-analog and all-digital facilities are not to be recommended while a hybrid facility combines the best features of each kind, namely the high bandwidth and ease of access of analog computers, with the high dynamic range, accuracy and nonlinear capability of digital computers.

## 5.2.1 An All-Analog Facility is not Recommended

Despite their first success in modelling dynamic systems, and their historic usefulness in simulating hydrofoils and submarines, it is felt that all-analog simulation facilities are becoming obsolete when either magnitude or complexity characterize a simulation problem. The highly nonlinear, complex nature of an ACV simulation study, as discussed in Chapters 3 and 4, presents a problem of such dimension that it is incapable of being solved using an analog computer exclusively without devastating simplifications. An analog computer is severely limited in dynamic range and in the ability to solve complex nonlinear equations. Most of the small array of nonlinear elements available on an analog computer are extremely expensive and not cost-effective at all. An analog computer system, consisting of several hundred integrators, amplifiers, and related analog devices is reasonably expensive (see discussion of analog computers in Appendix D) and incapable of solving the ACV problems without undesirable qualification of any results obtained.

## 5.2.2 All-Digital Facilities are not Recommended

All-digital computations can be employed for a problem of the scope of the ACV simulation project. Large scale digital computers are being applied to problems for which a few years ago a hybrid solution would have been recommended. However, one may deterrent to an all-digital facility is cost. To obtain the speed (and possibly extra core) required to perform a time-critical[*] real-time problem, a very considerable step in cost must be taken. There are several enhancements in simulation techniques that are not available with an all-digital facility. In t rms of overall performance one might be concerned at the outset about an all-digital facility's growth potential for handling high(er) fre-

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[*] "Time critical" means "where meeting the real-time requirements will tax the computer speed to its limit" or "where no idle time is left in the computational cycle".

quency problems. In addition, a time-critical real-time problem may place severe limitations on the large scale digital computer because the basic requirement is that the highest priority for CPU time must be given to the real-time task. This would very likely compromise the cost-efficiency of the digital computer because its operation would be reduced to one dedicated real-time task.

5.2.3 A Hybrid Digital-Analog Facility is Recommended for a Naval Simulation Facility

Hybrid computation has been applied to real-time tasks in ever increasing numbers for approximately ten years. At first the digital computer was considered a peripheral device intended to enhance the use of the analog computer. As the digital computer speed increased so did its role in hybrid computation. At the present time many medium size digital computers are installed as part of a hybrid facility. A considerable over-simplification is to state that in a hybrid facility the analog computer is used for the low accuracy, high frequency portions of one's problem and the digital computer is used for the high accuracy, low frequency portion of the problem. This may be the intent when one sets out to segment the problem, but usually the digital computer ends up carrying more than the originally planned share of the load.

The following advantages exist for hybrid users that are unique to their types of operation as opposed to all-digital operations:

1. The hybrid computer user has more "hands on" control of his problem than a user in a digital facility.

2. For interfacing prototype hardware to the simulation, the analog portion of the hybrid facility can be very useful. Sections of hardware can be modelled on the analog (or hybrid) and compared for performance against the test hardware.

3. Often the user will have an option as to computational methods to apply to a problem and consequently has more flexibility in general in a hybrid facility.

4. The hybrid computer properly configured and properly programmed should have a greater performance capability than either analog or digital computer alone. In the optimal limit the dynamic range of the hybrid computer should be that of its digital portion and the band width should be that of its analog portion.

5. At times small problems could be run on the analog computer concurrent with and almost independent of hybrid facility operations.

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The hybrid facility offers the user more overall performance, more performance per dollar, and greater flexibility than the digital facility. This situation may change in years to come, but one must bear in mind that, as digital computer capabilities improve, so will hybrid computer capabilities. A hybrid facility purchased now is unlikely to be significantly out-performed for many years, and no danger of concept or system obsolescence is expected.

5.2.4 A Medium Scale Digital Computer is Best Suited for the Digital Portion of a Naval Hybrid Simulation Facility

Selecting a digital computer of the proper class for hybrid operation is important. A small scale digital computer would do little but enhance an analog computer. Since word length for a small scale digital computer is typically 16 to 18 bits, most scientific calculations would have to be in double or triple precision. Core requirements would be high, speed reduced and flexibility virtually non-existent. Such a facility could only service a novice user for a short while or a user whose budgetary restrictions were so tight that no alternative existed. On the other hand, a large scale digital computer could handle the tasks of the digital portion of a hybrid facility. However, it is not a very cost-efficient computer to use in a hybrid facility. This is because real-time operation demands the highest priority for CPU operation. This would usually compromise the computational power of the large scale digital computer in terms of throughput rate. Furthermore, the task of interfacing a large scale digital computer to an analog computer and restructuring its operating system for hybrid operation would be very costly. This money would be better spent on a computer intended for real-time operation, where the operating system already exists. An analogy in using a large scale digital computer in a hybrid facility might be that of using a sledge hammer to drive a finishing nail.

For the above reasons, a high speed, medium scale digital computer is best suited for a Naval Hybrid Simulation Facility to be applied to ACV's and other crafts, boats or ships.

5.3 Necessity of a Multi-User Computer Capability

For any of the Navy programs that will use the Naval Simulation Facility, computer requirements or tasks fall within three categories:

1. Development of the real-time application programs (coding, assembly, compilation, debugging and linking of resident executive programs and the numerous subroutines needed for real-time simulation).

2. Actual real-time simulation of a Navy vehicle (ACV, Hydrofoil, submarines, etc.) for any one of the simulation end objectives (motion prediction, control design, visual simulation, sea trial support, etc.).

3. Other, non-real-time batch process jobs, for instance related to scientific calculations, stability analyses, control design, curve fitting, data correlation, etc.

For a specific Navy vehicle motion and/or visual perception simulation effort, these three types of requirements change in importance and in volume with time: category 1 tasks will be preponderant for possibly one year from the start of a simulation effort, while category 2 tasks will gradually mobilize the computer facility for the so-called "production runs"; category 3 would usually be interspersed between (1) and (2) tasks, depending on scheduling priorities. Clearly within a single Navy program such as a submarine simulation program, tasks (1), (2), and (3) are competing for computer time. The "bottlenecking" of computer use between competing tasks has been experienced at MIT over the years in the DSRV simulation effort and was resolved by the exclusive scheduling of activities and the scheduling of personnel to work at odd hours.

In fact, the single user dedication of the DSRV simulation facility was causing costly downtime and procrastination. In the case of the envisioned Naval Simulation Facility which allegedly could service several Navy progr. ms (ACV's for the AALC or Artic programs, Hydrofoils, Fleet or Advanced Submarines, ULMS, etc.) the problem of computer dedication and turn-around  e is compounded enormously. Furthermore, MIT's experience in this area is that a facility with an inherently single-user capability, which is funded primarily by one customer but used by several others — creates poor or intolerable scheduling situations. Unless care is exercised at the onset the computer facility will most probably be single task dedicated, i.e., the whole facility and its peripherals will end up being dedicated to a single task among the above mentioned categories (1), (2) and (3) for a single Navy program exclusive of all other tasks and other Navy programs. The resulting time lost by other programs and projects waiting for the computer to become available will create poor overall cost-efficiency. It is important to recognize that the greatest cost item often hidden or overlooked in evaluating a facility cost-effectiveness is the productivity of the people who will be running, programming

and using the computer facility. Furthermore, if one relates people's productivities to an expeditious solution to a specific task, it is clear that the mere dollar cost of acquiring and maintaining a computer and its peripherals is not alone the most important item in a cost-effectiveness budget.

For these reasons, it is important to implement a multi-access capability within the computer system. There are two ways to organize the hardware and software architecture of a computer for this purpose: the "non-interactive" (batch) and the "interactive" (time-sharing) multi-access.

### 5.3.1    Non-Interactive Multi-Access (Batch)

When operating concurrently with a real-time program, batch operation is the sequential servicing of another user. This servicing may be performed by a job scheduling feature of the monitor program under whose control all operations are performed. With the real-time program(s) operating in the "foreground" and batch operations in the "back-round", a much more useful facility can be obtained.

### 5.3.2    Interactive Multi-Access, or Time-Sharing

The second method to handle multi-user operations is by means of time-sharing. (A time-sharing terminal can usually also perform batch operations.) For our purposes time-sharing shall be defined as simultaneous multi-user access to a digital computer by means of simultaneous teletype communication in an interactive fashion. Basic features implied within this definition include:

- Program compilation and execution
- Text editing
- Text and data storage and retrieval

In the time-sharing mode the background user is in continuous communication with the computer. By the use of an editing routine he can sit down and write a program at a teletype while the facility is in full operation, and other users are almost unaware of his operation. Such operation is considerably more powerful than batch operation.

### 5.3.3 MIT Recommendation on the Multi-User Problem

It is unrealistic and eventually costly to ignore at the onset the multi-user problem for a Naval Simulation Facility which is slated to become an "open shop"*, to service several users within one or several Navy program(s). The multi-access problem must be addressed squarely even though this addition might appear as burdensome or undesirable to novice users of a new facility, or if the fact that funding provided mostly from a single Navy program might justify the casual treatment of this issue.

It is important to also realise that state-of-the-art computer technology now permits soultions, easily and in a cost-effective manner, to the challenge posed by a multi-purpose Naval Simulation Facility. The inc. ental hardware cost is justifiable when compared to the added performance, while the software cost is minimized since the computer vendor carries the burden of developing the operating systems for a multi-user capability. It is possible that one user's real-time problem would become sc demanding of computer time that all other users would be locked out. This situation should be considered as an extreme case and its occurrence, although possible, should be viewed as not typical and continuous. Although the Navy programs that will use the hybrid facility may have considerable similarities, one must assume that they will require essentially separate user software. Consequently, many programmers are likely to want to compile (or assemble) during a period where another real-time task is being executed. Further, one user may want simultaneous compilation (or assembly) of one or more programs and execution of still another.

MIT recommends that specific plans be made for a multi-access capability. Consideration of performance-to-price ratios with available funding resources will dictate if batch operation or a time-sharing multi-access should be implemented. MIT's feeling is that a powerful, time-sharing real-time system should be strived for — staggering in time the acquisition of necessary extra core and user terminals if necessary. It appears that this will constitute a cost-effective and promising investment — in

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* In an "open shop" facility, customers use provided equipment to solve their own simulation problems, with support as required supplied by the simulation facility staff. In a "closed shop" facility, the simulation tasks are submitted to the facility staff who will program and run it. The problem submitter analyzes the results.

fact, it not only permits software development and support from different time-sharing terminals within the confines of the facility, but also from terminals located far from the Naval Simulation Facility through telephone lines.

5.4    Assumptions and Broad Guidelines for Implementing a Naval Hybrid Simulation Facility

In order to conduct a computer investigation and provide meaningful recommendations, it is not sufficient only to review the computer industry and consider the specific end simulation objectives of one or several Navy programs. It is also important to consider the environment in which the simulation facility will be used. For the purpose of enabling a timely investigation, the following assumptions (correctly or incorrectly) were made:

1. The Naval Simulation Facility user is quite knowledgeable and experienced in the use of analog computers.

2. The user has limited experience in digital computer operation.

3. The user has virtually no experience in the use of a hybrid computer.

4. A proposed Naval Simulation Facility should be operational in approximately one year from start of implementation.

5. Several Navy groups and programs will each require considerable hybrid computer time and every attempt should be made to maximize the amount of computer use each "customer" is given.

6. Turn-around time from simulation configuration to another simulation configuration should be minimized.

7. At some point one or more of the computer configurations is going to become time-critical.

8. An "open shop" facility arrangement will exist after the first year (or less) of facility operation.

9. Computer selection should keep open the option of future expansion of both analog and digital equipment suite size.

What is therefore required is a computationally powerful hybrid computer, to be operational in a very short period of time, to be used for solving sophisticated problems by a team of intelligent but initially inexperienced

personnel. By proper planning and execution, this can be accomplished.

## 5.5 Selection of the Analog Portion of a Naval Hybrid Simulation Facility

### 5.5.1 Use of Surplus Analog Computers

Analog computers that fit the needs of a Naval Hybrid Simulation Facility may be available as government surplus. Care should be exercised before following such a route, and the use of available, old vintage analog computers must be weighted against the following disadvantages:

1. Old or available analog computers may not offer a capability or fast reconfiguration and checkout necessary in a multi-purpose Naval Simulation Facility.

2. Old or available analog computers may not offer the high degree of reliability necessary in an efficient Naval Simulation Facility.

3. Several identical analog consoles are needed in a mult-purpose Naval Simulation Facility, mostly for standardization of programming, interfacing, maintenance and troubleshooting. Chance procurement of surplus analog computers may not satisfy this requirement.

4. To "hybridize" an old analog computer may be costly.

### 5.5.2 Desirable Features in a Modern Analog Computer

The following general features are considered necessary for analog computer use in a Naval Hybrid Simulation Facility:

1. The computers should be of modular design and enable the user to purchase a computer sized to his immediate needs and to easily expand at a later date if required.

2. They should be all solid-state so as to reduce maintenance and increase reliability.

3. The computer must be purposely designed to operate in a hybrid environment.

The following hardware additions are considered mandatory when an analog computer is to operate in a hybrid environment:

1. Solid-state, binary-coded address selection system. It allows the digital computer to select and read any addressable analog component or trunk; also it allows digital computer the capability to select, set and ve any potentiometer (servoset or a digitally controlle attenuator (DCA) located in the analog computer system).

2. Solid-state mode control circuitry. It allows the digital computer the capability to send as well as receive mode signals from the analog computer.

3. Extensive patchable logic systems. It allows an extended path of communication with the digital computer in terms of discrete timing synchronization or simulation control information.

Some manufacturers (Electronic Associates Inc., Applied Dynamics, Inc.) claim that their computers can be expanded later to include automatic patching. MIT/Draper Laboratory considers this feature less important in the ultimate selection of a computer.

5.5.3 Analog Computer Candidates for a Naval Simulation Facility

Due to the present economic climate several analog computer manufacturers have recently folded. There are now three American manufacturers worth considering for the analog computer portion of a Naval Simulation Facility. These are:

1. Applied Dynamics, Inc., Reliance Electric Company, Ann Arbor, Michigan.

2. Electronic Associates, Inc., West Long Branch, New Jersey.

3. Hybrid Systems Division of Digital Resources Corp., Houston, Texas.

These companies have been involved in placing their analog computers in a hybrid environment for several years. The analog computers investigated by MIT/Draper Laboratory are:

| | |
|---|---|
| Applied Dynamics | AD-4 |
| Electronic Associates, Inc.* | EAI 680, EAI 7800 |
| Hybrid Systems | SS-100 |

All computers are 100 volt computers with the exception of the EAI 680, which is a 10 volt computer. It is generally true that a 100 volt analog computer will have a larger amplitude, dynamic range than a 10 volt analog computer. Nevertheless, it was decided to consider the EAI 680

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* The EAI 8800 was not considered because it is no longer in production (although still available new) and its cost is very high compared with the EAI 7800.

on the condition that if all other considerations proved equal and a substantial benefit in cost was not to be realized, the EAI 680 would be dropped from further consideration. Such was the case, so the EAI 680 was dropped.

### 5.5.4 Comparison of Analog Computer Candidates

In order to compare the cost of the four computers in a meaningful manner an equipment complement was established that each computer could supply. For the evaluation of the analog computers, see Appendix D.

Special emphasis was put by MIT on the computer features specific to hybrid operation. Other analog computer features that MIT considers unnecessary when the analog computer is used in a hybrid environment were not considered as part of the comparison between the different vendors.

Since the user survey uncovered no major deficiencies in any of the considered analog computers and none was found to be particularly outstanding in either its specifications, options or growth potential as opposed to its competition, one must conclude that any of the four could be used as part of the hybrid computer facility. Service and cost are therefore the basis for analog computer selection. Based on manufacturer suggested price and the MIT cost-benefit ratio, the AD-4 and EAI 7800 are more cost-effective than the SS-100. In addition, service for the SS-100 might be more difficult to obtain due to the concentration of SS-100's in the southwestern part of the United States and apparent lack of facilities elsewhere.

### 5.5.5 Hybrid Interface Vendors

Consideration should be given to having the analog vendor supply the hybrid interface system (analog-to-digital converters, digital-to-analog converters, discretes, etc.) since in general he is more experienced than the digital vendor in this area, and has installed more hybrid installations. The interfacing task typically winds up being a problem of both grounding structure and noise. These problems are encountered more often in an analog system than in a digital system and as such usually can better be handled by an analog computer vendor. Furthermore, analog vendors usually are willing to take total system responsibility, i.e., responsibility for analog and digital computers and hybrid interface. (Ther may be certain combinations of analog/digital computers that have not operated as a hybrid system previously, or certain digital computers for which an

analog vendor does not want to assume system responsibility.) Caution should be taken with respect to this consideration. The analog vendor is usually not in a position to support the user without backup support from the digital manufacturer. This backup support may not be forthcoming in the case when the digital vendor is not directly involved with the purchase of the digital computer.

5.6    MIT Recommendations for an Analog Computer for a Naval Simulation Facility

A search should be conducted in government surplus equipment to see if two reasonably complemented, solid-state 100 volt analog computers could be obtained. This cost of hybridizing these and their inherent features should be compared with the advantages of procuring a new analog computer specifically designed for hybrid operations.

A decision to buy one or several new analog computers will probably be reached. Consideration should be given to purchasing two half-expanded* analog computers rather than one fully expanded one. Although the cost for the one fully expanded analog computer would be slightly less, the split arrangement has two major advantages:

First, the capability to run more than one hybrid task should be striven for and this is impractical with only one console. In fact, each hybrid task should have its own separate analog computer patchboard. Two consoles would therefore have the potential to handle two distinct users. To avoid problem dedication to one analog computer, equipment suites should be kept identical.

The second advantage of the two console approach is its growth potential. Small increments of expansion are possible with this arrangement, whereas small expansions would be impossible (by definition) in the fully expanded system. Space and other facility allocations designed around the two console concept represent far better planning.

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* Note : "Expanded" or "partially expanded" analog computer refers to the degree of completeness and number of devices that are accommodated by a given analog console. A console is designed to accommodate a certain maximum number of operational amplifiers, integrators, function generators, resolvers, multipliers, etc. An analog computer may be purchased with less than the maximum allowable number of devices.

Since the three reviewed analog computers are nearly equal in overall ability the selection of analog equipment should be based on price and service. Consequently, based on price, MIT recommends the AD-4 analog computer system as the first choice for the ACV Simulation Facility. In the event that Applied Dynamics cannot adequately service the facility site MIT recommends the EAI 7800 system as the alternate choice. (It is possible that discounts are available for the AD-4 or EAI 7800, but neither manufacturer so indicated.)

As a further recommendation MIT believes that each analog computer in the recommended dual system have a complement as outlined in Table D-2 of Appendix D. The cost of the two AD-4 systems would be $410,000 as compared to $500,000 for the two EAI 7800's.

## 5.7 Selection of the Digital Computer Portion of the Hybrid Facility

### 5.7.1 General Selection Criteria

A search was launched for a cost-effective, high speed, real-time oriented multi-access, medium scale digital computer. Three sets of structured criteria were established by MIT: computer features considered necessary; features considered desirable; and finally, criteria applicable to the computer cendor. One is looking for a mixture of hardware, software and operational services by the vendor to be successful over the life cycle of the simulation facility.

#### 5.7.1.1 Necessary Computer Features

1. The selected computer system should be a proven one. A new computer on the market, that represents a new design, with new software should not be retained because of the high risk involved. It usually requires one to two years of customer operation to get the bugs out of a new computer system. Normally these bugs are mostly software rather than hardware in nature. However, a new computer that is upward compatible to a computer of established capability (with respect to both hardware and software) should be acceptable.

2. A growth potential must be offered in core, I/O's, user access and speed by means of modular additions.

3. The CPU should have a high speed. This demands a memory cycle time of at most 1.5 microseconds. It was felt that any computer of slower speed would prevent the growth potential required for simulating Air Cushion Vehicles of gradually more sophisticated models or distributed models of suction forces for submarines.

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4. Floating point hardware must be available.

5. The computer should have a word length no less than 24 bits. This rules out any mini-computer and in fact the smallest word length for any of the computers under consideration is 32 bits.

6. A proven real-time operating system must be available, capable of supporting the operation of a real-time problem program using FORTRAN.

7. The strict minimum core size should be 32 K. (This minimum core size is predicated on a DSRV type simulation which had no parameter distributed models and had been written in compact, efficient machine language.) Vendor monitor sizes, multi-user requirements and/or visual simulation requirements indicate that 64 K is the desirable minimum core size for the Naval Simulation Facility.

8. An external priority interrupt structure must exist.

9. The following hybrid interfaces should be the minimum allowable* :

   ● Digital to Analog Converters –
   　　32 DAC's, 10 Volt, 11 bits and sign

   ● Analog to Digital Converters –
   　　32 ADCON's, 10 Volt, 11 bits and sign

   ● 20 Sense Lines

   ● 20 Control Lines

   ● Parallel Data Input Register

   ● Parallel Data Output Register

5.7.1.2  Desirable Computer Features

Other features that the MIT Draper Laboratory considers desirable include:

1. Rapid response to external interrupts, and an efficient priority interrupt structure.

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* The digital vendors were asked to price out an interface, not withstanding a ‥ ‥ ‥ous comment concerning analog vendors performing the inter-f ‥ ‥ task. The user should determine which of the two vendors would do ‥ better job of building the hybrid interface, and in the case of equal (or nearly equal) ability choose the low bidder.

2. Interleaving of memory, which can result in a considerable reduction in program execution time (not applicable to synchronous machines).

3. A substantial number of general purpose and index registers so as to minimize programming gymnastics.

4. Multi-port memory, which allows for greater efficiency in using input/output devices than for a single-port memory.

5. Small increments of core expansion. If core expansion is required, for whatever the reason, being able to expand in small increments of core will obviously result in a savings of money.

5.7.1.3 Screening Criteria Applicable to Computer Vehicles

The selected computer vendor should have adequate experience in hybrid, digital-analong operations, since his previous "hybrid" awareness will preempt many problems and enable him to better support the Naval Simulation Facility. A computer service network should be available near the site location of the Naval Simulation Facility to provide periodic preventative maintenance of digital peripherals such as line printers, magnetic tape units, disks, etc., usually on a weekly basis.

5.7.2 Computer Candidates

MIT/Draper Laboratory held discussions with nine digital computer manufacturers concerning the use of their computers as part of a possible Naval Simulation Facility to simulate Air Cushion Vehicles. These manufacturers in alphabetical order are:

- Control Data Corporation (CDC)
- Digital Equipment Corporation (DEC)
- Electronic Associates, Inc. (EAI)
- Honeywell Inc.
- International Business Machine (IBM)
- Radio Corporation of America (RCA)
- UNIVAC
- Xerox Data Systems (XDS)

5.7.2.1 Preliminary Screening

During these meetings with vendors, MIT/Draper Laboratory described typical computer requirements for the simulation of Air Cushion Vehicles to be undertaken on behalf of the Navy. Each vendor was given a Request for Information (RFI) form to respond to (see Appendix D for a copy of

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the RFI). Considerations such as general features and objectives, estimates of core size, cycle time and cost were discussed with each vendor so that they could determine the class or family of their computer line that would be applicable to an ACV simulation effort.

Two vendors, UNIVAC and RCA, verbally informed MIT/Draper Laboratory that they would not be able to respond to the RFI since neither vendor had a computer that could fulfill the requirements.

A third vendor, EAI, replied to the RFI in letter form stating that due to production difficulties the one computer that might be worthy of Draper Laboratory's consideration would not be available until June 1972, at the earliest. In its place they suggested a configuration that MIT feels is unsatisfactory.

The remaining five manufacturers responded with a cumulative total of seven digital computers as follows:

- CDC          3600
- CDC          3200
- DEC          PDP-10
- Honeywell    H632
- SEL          8600
- XDS          Sigma 5
- XDS          Sigma 8

### 5.7.2.2   Equipment Configuration

The vendors were given the freedom to configure an equipment suite for an ACV simulation hybrid facility which they felt represented a typical installation complement. Where possible, equivalent capabilities were striven for. Since the ultimate user for the Naval Simulation Facility had not been defined at the time of the MIT meetings with the vendors, the requirements of a real-time monitor were not imposed on the vendor. However, the vendors were asked to include discussions of the various monitors that were available with their computers.

### 5.7.2.3   Monetary Guidelines

In order to establish monetary guidelines for the vendors a practical limit of one million dollars was suggested for the digital computer and hybrid interface. Vendors were told that they could prpose equipment

beyond the one million dollar limit if in their opinion the more expensive
systems sufficiently enhance the facility cost-effectiveness. No vendor
in fact responded beyond that limit. Purchase versus rental or leasing
issues were not considered in order to simplify the relative comparison
between vendors. Only the purchase option was retained for simplicity.

5.7.3    Reduction to Three Computer Candidates -- Mutual Comparison

Appendix D (Section D.2.2) gives the details of the selection process. It
is shown there how the number of candidates for the digital portion of a
Naval Hybrid Simulation Facility is narrowed to only three candidates :
the SEL 8600, the XDS Sigma 8 and the DEC PDP-10 with KI-10 processor.
Any one of the three could be retained depending on the emphasis on user-
needs and the kind of rationalization that one is willing to adopt. One must
carefully weigh the immediate advantages and future potential advantages
of each computer with the disadvantages and/or risks. In any event a
contract written with any of the vendors must contain pe·formance guaran-
tees and a milestone schedule to which that vendor must be willing to
adhere. The contracting of the facility acquisition undoubtedly will play
an important role. The following is a short summary of the features of
each computer candidate resulting from in-depth studies of the systems
conducted through the vendors and actual uesers. Appendix D, Section D.2.3.
gives more detail as well as users' comments which helped in generating
this synthesis.

5.7.3.1  The SEL 8600

Despite being the smallest of the three computer companies and being
comparatively new to the medium scale computer field SEL has come up
with a very good computer and has demonstrated an ability to adequately
service both the hardware and the software of their users. They have a
highly successful background of interfacing computer systems. Besides
offering the lowest price for competitive hardware, it is believed that
the SEL 8600 computer would prov: ·: the most attractive no-cost extras
of the three candidates. The SEL Real-Time Monitor and FORTRAN
compiler when debugged should be extremely efficient. Considerable
effort is being made to support both these items and minimize the risk
to a buyer.

The SEL Batch Processing System (BPS) has apparently been sufficiently
debugged to be called useable. However, the Real-Time Monitor (RTM)
is new to the field. In fact, only one user was found who was employing

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RTM and he was not using the salient features that would be needed for simulating Air Cushion Vehicles or other Navy crafts. That user was confident of the RTM's eventual success and is highly dependent upon its use in the immediate future. Notwithstanding that user and his comments, the SEL RTM is untried and unproved. Users of SEL's FORTRAN have felt its eror package is minimum and needs considerable improvement. Documentation and training are good for the first generation but not as good as they would be from XDS or DEC, or as they will be. How improved these items would be when the Navy would need them is unknown. Although it is possible that SEL is considering adding time-sharing capabilities to the 8600, for this study it is assumed that no time-sharing exists or will exist when required for a Naval Hybrid Simulation Facility.

In summary, SEL's hardware offering is the best price-performer of the three considered (and in fact of all reviewed in this study). On the negative side, lack of time-sharing capability and the newness of their monitor and the FORTRAN may detract from effectiveness.

### 5.7.3.2  XDS Sigma 8

The XDS Sigma 5 computer has proven hardware and software but it is unlikely to be capable of supporting more than one heavily time-consuming real-time task and background operation. The Sigma 8 computer which XDS has announced is available at the end of 1971 is considerably faster than the Sigma 5 and XDS claims its software to be compatible with the Sigma 5.

The Sigma 5 real-time monitor is operating in the field doing real-time foreground with batch background. XDS claims time-sharing capabilities with this monitor. Documentation and training are well established. XDS has two FORTRANs : one for fast compilation and one for fast execution, offering the user the flexibility he needs. The XDS FORTRAN is considered to have as good an error diagnostic package as exists in the field. The XDS FORTRANs have been designed to be compatible with virtually everyone else's FORTRAN, a very worthwhile feature.

On the debit side XDS's service record has been very spotty. User support, in both the hardware and software area, has been lacking at times. The MIT/Draper Laboratory reviewing group has been using XDS equipment for four years and its experiences have been similar to those of the users we surveyed.

For a while, the MIT facility seemed to have been a training site for new XDS service personnel. While MIT's demands for better service may have finally had an effect, the improved service situation is primarily due to changes of personnel. This implies that the user's service for the envisioned Naval Simulation Facility may depend more upon good fortune in having concerned personnel in the right position, than in a well worded service agreement. XDS training of some of their users has sometimes been poor.

In short, the XDS Sigma 8 is a very promising computer and XDS can support a facility. On the negative side remains their poor service record and lack of experienced real-time, time-sharing RTM users.

### 5.7.3.3 The DEC PDP-10 with KI-10 Processor

The PDP-10 with KI-10 Processor is not an announced computer. DEC informed MIT/Draper Laboratory that a formal announcement for this computer, hereafter referred as the PDP-10I, will take place around September 1971 with release in the fall of 1972.

As is the case for the XDS Sigma 5, it is felt that the PDP-10 will be incapable of handling heavy real-time operation with background operation. If DEC's claim of speed enhancement for the 10I is correct it should sustain such operation. The excellent time-sharing capabilities of the PDP-10 would be virtually unused if every day real-time user(s) locked out the background. It is felt that the PDP-10 could be used as an interim computer until the PDP-10I became available, assuming satisfactory arrangements as to cost and delivery of a PDP-10I could be made. The following comments relate to the PDP-10I as extracted from PDP-10 operations.

The PDP-10 has been properly supported by DEC and the result has been that their users are so pleased that they sound like DEC salesmen. Ironically, many non-DEC equipment users candidly admitted that, put in perspective, their decision not to use DEC equipment was probably due to lack of aggressiveness on the part of the DEC sales organization.

The TOPS-10 monitor has been designed with real-time operation in mind. Time-sharing in a real-time environment has been a DEC objective and they continue to expend effort in this area. An updating of the monitor for the PDP-10 (compatible with the 10I) is already in the works and scheduled for release before the 10I release.

Many improvements that a user would want if he were purchasing a PDP-10 reportedly will be available in the 10I. For example, the PDP-10 does not have double precision floating point hardware, whereas the PDP-10I does. Since the PDP-10 is a 36 bit computer, and most of its competition a 32 bit computer, DEC felt that often what other computers had to do in double precision, the PDP-10 could do in single precision. They have an additional 18% of accuracy available in their single precision than most of their competition does. Also, an optional optimizing second pass will be available for FORTRAN compilation (in about one year). This would allow the user to compile and edit without the second pass and, when his program has been debugged, to use the optimizer pass.

DEC's FORTRAN is not as compatible with other users' FORTRAN as XDS's is. Their error messages are not nearly as good as XDS's either. Their present FORTRAN allows negative subscripts as well as negative going subscripting. Consequently, in operation, a check for subscripts, even if these latter features are not being used, is made when not required. The result can be slower operation than necessary for calculations with monotonic, heavy subscript notation. The optimizer pass is intended to rectify this.

DEC has built two prototypes of the PDP-10I. Before final selection of a PDP-10I for a Naval Simulation Facility, further assurance should be obtained from DEC as to the availability of an interim PDP-10.

In summary, the PDP-10I promises to be the most versatile of all computers investigated. Its availability for a Naval Simulation Facility within the time frame required would have to be guaranteed.

5.7.4  Recommendations on a Digital Computer for a Naval Simulation Facility

A computer selection should be made that considers operations over at least five years. If one does not build the needed growth potential into the facility, its ultimate usefulness will be reduced. The MIT/DL recommendation on the digital portion of a hybrid simulation facility is structured in the following points :

1.  If operations are to be limited to one or more real-time tasks without background operation, the SEL 8600 would be the most cost-effective choice.

2.  For real-time foreground and batch background, none of the three computers that were retained has been found clearly superior to its competition. In fact one would have to view a formal proposal from each vendor and trade-off costs and capabilities.

3. For time-sharing operations concurrent with real-time operation, the DEC PDP-10I would be best suited. Should DEC be unwilling or unable to satisfactorily assure the Navy of the PDP-10I's availability, the XDS Sigma 8 should be selected.

MIT's recommendation on the computer multi-access issue is that a powerful time-sharing configuration should be strived for eventually. Navy plans and resources should be carefully considered in the light of what a synergetic approach can offer when the needs and resources of different programs are pooled together.

The equipment suites that each vendor suggested should be modified when a formal proposal is sought. For example, a CRT display connected to a teletype is an extremely useful arrangement but none was suggested. Also, SEL suggested purchase of a card reader of their own manufacture and one would surely prefer that of another manufacturer. The proposed equipment complements listed in Appendix D were intended to reasonably illustrate cost and should be viewed accordingly.

## 5.8 Recommended Steps towards Implementation of a Naval Hybrid Simulation Facility

To meet the goals established and in order to implement a Naval Simulation Facility, the following preliminary steps should be taken:

1. Make a final selection of hybrid computer components (so that the proper personnel can promptly begin their training in use of the selected computers).

2. For the analog portion, implement the dual, partially expanded consoles.

3. The training should be sufficiently broad and should be undertaken when the personnel have demonstrated that they will not be in "over their heads". There is no point in rushing into a training course without adequate preparation on the part of the trainee. Since time to learn to use the facility is not overabundant, it is necessary to undertake the training very judicially.

4. User programming should initially be written using floating point format, in FORTRAN. The universality and ease of programming in FORTRAN will allow the facility to start operation much sooner than if assembly language programming is used.

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5. As system confidence rows and hybrid user skill develops, assembly language should start being used where required. For the computers under consideration fixed point arithmetic is from 50 to 100 percent faster than corresponding floating point arithmetic. Assembly language operational improvements are a function of the ability of the individual programmer and the efficiency of the code developed by the compiler used.

6. Training with multi-access capabilities of the monitor should begin. Modification of the standard monitor to suit the specific facility requirement must be done. Familiarization with actual system should begin.

7. Vendor training should be supplemented by support from an experienced hybrid user. The purpose of the latter support is to assist in setting up efficient system operation. Many of the techniques of hybrid operation could be obtained by such support.

For a more detailed schedule of events, including computer delivery and acceptance, see the milestones of Appendix A.

# APPENDIX A

## MILESTONES AND ACQUISITION PLAN
## FOR A NAVAL SIMULATION FACILITY
## APPLICABLE TO ACV'S

This appendix summarizes the plans for acquiring the building blocks leading to an ACV Simulation Facility. It is presumed that the computer and visual-kinesthetic equipments are also applicable to the simulation of other Navy crafts, boats and ships.

### A.1 Milestones and Plan for Updating ACV Mathematical Models

The appended fold-out chart gives the envisioned activities and their time-spread. Most items require relatively short amounts of time for implementation, except for the derivation and programming of non-amnesic ACV equations of motion, which is estimated to take about two years before reliable and useful outputs can be generated. (Appendix B gives a breakdown of manpower estimates.)

### A.2 Milestones and Plan for Acquiring a Computer Facility

The appended fold-out chart contains a plan for acquiring a hybrid simulation facility. If prompt actions is taken on component selection, hybrid simulation operations for at least one Navy program could start about one year's time after the beginning of the acquisition effort. Note that five (5) months are assumed between the release of purchase order and delivery of computer, an assumption that has been verified with the concerned vendors. If a less advanced computer (Sigma 5, PDP-10) is delivered in the interim whi.. _ ..ore advanced version is being produced (Sigma 8, PDP-101) particular attention must be given to the vendor's progress and his own milestones should be monitored.

Note that the user software (ACV ULMS, etc.) can be written in FORTRAN very early by personnel not necessarily among the simulation facility staff with compilations made on any system with a compatible FORTRAN compiler. The FORTRAN software should help during the computer acceptance and facility familiarization phases.

Finally, acceptance of multi-access features should be made part of the overall acceptance test package. Familiarization and actual use of the multi-access features by facility staff can occur somewhat later.

A.3      Milestones and Cost Estimate for a Visual and Kinesthetic Simulator

The estimated acqustion schedule and costs are shown below. The major pacing item in the schedule is, of course, the scene generation processor. Of the two prospective vendors for this item, namely G.E. and Evans and Sutherland, the latter appears to be in the best position from a technical and price standpoint. The main reason for this is that they are benefitting from more recently developed algorithms. They are in the process of producing the first system with the techniques proposed herein for the ACV simulation, having previously utilized a less sophisticated line model technique. There is thus a certain question at this point of their successfully producing the system as described; however, because of the work they have already done, the confidence level is relatively high.

In comparing the two vendors, not only is the scene quality superior with the Evar  and Sutherland technique, but the price comparisons are approxim.   ιy $ 1.7 million for the G.E. System for three channels (.7M for one channel) versus .5 to .6 million for the Evans and Sutherland system for three channels (.4 - .5 M for one channel). By this fall all the first system should be completed at Evans and Suthe land, so further evaluation can be made at that time.

In cost estimates for the scene generation processor and projector equipment are based on a monochrome system. Subsequent conversion to a color system, if desired, would cos. an estimated $ 100 K for the scene generator and $ 65 K for conversion of the projectors. The estimate made by Evans and Sutherland for the scene generation mcdification was indicated as being very approximate at this point and probably overly conservative. A more accurate estimate will most likely be available in several months. The estimate for the projectors is based on factory modification of the monochrome units.

Assuming that the Evans and Sutherland system would be procured, the delivery after receipt of order is estimated at 9 to 12 months. It is estimated that the procurement cycle from initial review of the requirements through submittal of request for quotes and the final placement order would be approximately 5 1/2 to 6 months. The total delivery time for the scene generation processor would thus be on the order of 18 months. All other procurements would be of shorter duration than this, and the times indicated on the schedule for each of these should allow for the timely acquisition of the overall visual simulation facility.

Table A-1 shows a cost breakdown for a visual-kinesthetic simulator.

Table A-1

Cost Breakdown for a
Visual-Kinesthetic Simulator

| Item | Man-Months | | Hardware Costs |
|---|---|---|---|
| | Staff | Hourly | |
| Scene Generation Processor | 12 | | 550 K |
| App'l Comp. Memory | 1 | | 25 K |
| Software | 4 | | |
| Kinesthetic Motion Platform | 25 | 17 | 45 K |
| Projection Equipment | 6 | 3 | 88 K |
| Installation and Integration | 5 | 5 | |
| Acceptance Testing | 1 | 1 | |
| Totals | 54 m/m | 26 m/m | 708 K |

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# APPENDIX B

## AN EXPERIMENTAL AND ANALYTICAL PLAN
## FOR DEVELOPING AN
## AIR CUSHION VEHICLE MATHEMATICAL MODEL

This section gives a step by step timetable and allocation of personnel for the necessary ACV mathematical model development.

Task 1 : Extension of perturbation methods for steady and sinusoidal excitation analysis and programming for simulation.

| | | |
|---|---|---|
| 1 Engineer | : | 1/2 years |
| 1 Programmer | : | 1 years |

Task 2 : Analytical development of temporal convolution integral approach for use in simulation model.

| | | |
|---|---|---|
| 1 Engineer | : | 1 1/2 years |
| 1 Programmer | : | 2 years |

It is recommended that these people work closely (same office) with those in Task 1 above so that overlap in programming is avoided, particularly in the use of contractor supplied data.

Task 3 : Seaway simulation in conjunction with Tasks 1 and 2 above.

a. Sinusoidal Sea

1/4 Engineer year
1/4 Programmer year

b. Spectrum Generation

   1/8 Engineer year
   1/8 Programmer year

c. Modelling of Refraction and Steepening in Surf Zone

   1/8 Engineer year
   1/4 Programmer year

Task 4 : Adaption and programming of contractor supplied
         data on fan characteristics, skirt and plenum
         characteristics, thrusters and effectors.

   1/2 Engineer year
   3 1/2 Programmer years

Task 5 : Experimental check of pressure distribution
         under models.

         2 models
         3 loading conditions (pressures)
         2 gap sizes
         2 pitch angles ($0^o$ and bow down)

Total of 24 tests plus building of table with
manometers built in.

         1/4 Engineer year
         1/4 Technician year

         Materials and Travel $\approx$ $ 1000

Task 6 : Maneuvering Model Tests

         a. Planar motions ~ at 3 bases
            Yaw angles $0^o$, $45^o$, $90^o$

         b. Rotating arm at the same 3 base yaw angles

Task 7 : Drag Testing

         a. Some straight ahead drag tests have been
            made. If the data looks reliable there is
            still the necessity to run tests accelerating

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the vehicle to determine the validity of the quasi-steady analysis.

## Task 8 : Seaway Testing

It is highly recommended that model tests be run in a seaway at various yaw angles. The purpose of this is to check the validity of the analytical models described earlier rather than to provide direct input to the simulation. The range of operating conditions is far too great to use experimental data directly.

Included under the general classification of seaway testing are the following types of test:

a. Oscillating the models in calm water to determine the relationship between vertical place restoring forces and phase and exciting frequency.

b. Running the models in regular waves at random speeds with the model fixed to determine the relationship between frequency of encounter, wavelength, wave height (limitations of linear assumption) and the exciting forces.

c. Running the models in regular waves with restraint only in surge to check motions simulation.

d. Running the models in an irregular sea.

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## Model Test Facilities

The various institutions which are capable of handling the experimental work required by this project were contacted. All concerned were interested in the project and a breakdown of their capabilities follows. None were eager to make specific cost estimates without a formal RFP procedure. The author was unwilling to commit either the Navy or MIT to this at this preliminary stage. The work required is estimated to tie up any facility for approximately one month.

The following facilities were contacted on August 3, 1971. Inquiries were made concerning testing capabilities and availability of facilities. All facilities listed were reported to be available for use.

a. University of Michigan
   Ann Arbor, Michigan
   Person contacted : Mr. Snyder    (313) 764-9432, 764-9438

   Resistance and propulsion tests

   Tank: length 360 feet
         width    22 feet
         depth    12 feet maximum, 8 feet average

   Carriage top speed is 20 ft/sec with approximately
   150 feet of steady state run.

   Maneuvering tests

   Tank: length 100 feet
         width    60 feet
         depth     6 feet

b. Stevens Institute of Technology
   Hoboken, New Jersey
   Person contacted: Professor Savitski  (201) 792-2700

   Rotating arm facilities are available, as well as facilities for
   drag tests and pressure distribution tests.

   No planar motions mechanism is available.

c. Hydronautics, Inc.
   Laurel, Maryland
   Person contacted : Mr. Gertler  (301) 776-7454

   Facilities for excitation analysis -- steady and sinusoidal

   Facilities for seaway simulation — regular, irregular, surf

   Drag testing facilities

   Maneuvering tests — planar motions facilities — no rotating
   arm facilities are available.

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d. David Taylor Model Basin
   Naval Research and Development Center
   Carderock, Maryland
   Person contacted: Dr. Feldman (202) 227-1242

   Facilities — known to the Navy

   This facility is actively involved in the AALC project and is
   initiating horizontal plane calm water tests of the type described
   on a budget of approximately $100,000 to $125,000. Extension
   to similar work in the vertical plane would require additional
   expense of the order of $75,000. Wave test facilities are avail-
   able.

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# APPENDIX C

## AN "INVERSE PROBLEM" TECHNIQUE
## FOR USE IN CONJUNCTION WITH
## FULL-SCALE VEHICLE DATA
## OR NON-CAPTIVE SCALE MODEL DATA

C.1    <u>General Considerations</u>

The "inverse problem" of a dynamical system, as opposed to the "direct problem" of predicting its motion from a given structure and from given inputs, involves the reconstruction of its structure with quantitative estimation of its parameters from observed motion and given inputs.  For ACV's this amounts to estimating quantitative values for the coefficients entering a given set of standard equations of motion.  Many methods have been devised for this purpose, and a review of the state-of-the-art in systems identification techniques could reveal the following approaches: numerical deconvolution, spectral density, sinusoidal response measurement, learning models and "analog matching", Weiner modelling of nonlinear systems, gradient techniques, quasi-linearization and various forms of optimal control and filtering techniques.

It is characteristic of ships, ocean vehicles and free-running side models in towing tanks that the observed motion data is contaminated with noise, both due to stochastic disturbances in the dynamic process itself (ocean waves, random vibrations and turbulent air flows) and due to the measurement.  In a filtering theory, the latter is referred to as "measurement noise" while the former is called "driving" or "process noise".

For non-captive scale model tests of ACV's, or for full side trials of the ACV's to be conducted by Bell and Aerojet, it is felt that a coordinated and well prepared plan of data analysis and reduction is necessary.  For eventual correlation of the a priori mathematical model, a solution to the inverse problem is necessary.  Recent studies have applied a deterministic method to the identification problem of surface ships [1].  Similar and other techniques are also planned for a broad vicinity of ocean vehicles. MIT's experience and recommendation in this area is that the driving

noise and measurement noise should be explicity accounted for by the identification technique to be utilized, and in particular, that quantitative bounds and confidence levels be also given for whatever estimates output is yielded. This practically rules out deterministic methods for the ACV inverse problem, a recommendation also justified by apparent difficulties encountered in identifying coefficients for surface effect ships. Fortunately there are system identification methods that can be applied to the ACV inverse problem [3,4,5,6,7]. Of these, Kalman filtering is a promising and po erful tool, which MIT is recommending.

In the last two years, research was conducted in the MIT Ocean Engineering Department on a general identification method applicable to ocean vehicles. The results recently obtained are extremely encouraging. The method is flexible and seems to be quite general; it can identify linear and nonlinear coefficients of submarine and ship-like dynamical systems. It can be applied successfully to the ACV inverse problem.


C.2        System Identification by Kalman Filtering

The following is a brief description on how Kalman filtering could be used for the ACV inverse problem.

Kalman filtering is a method that provides optimal filtering of the state variables of a dynamical system driven by random disturbances, for which only incomplete and noisy measurements are available. The theory is strictly valid for linear systems and Gaussian inputs. It is applicable, at least in a heuristic sense, to any system that can be linearized reasonably and for which driving disturbances (sometimes called driving noise) and measurement noise are zero mean and for which mean values and covariance statistics are reasonably available. If continuous measurements are available, the increments between measurements can be made arbitrarily small and the linearization can always be justified. Such is the case for the ACV dynamical system, where the wave disturbances constitute the driving noise and measurement noise is particularly present in the air pressure data.

There are several ways of implementing Kalman filtering for system identification. A straight-forward and useful one is the so-called state-augmentation technique. An unknown coefficient or parameter can be estimated by treating as a state variable itself (called pseudo-state variable) the increment $\Delta p$ to be added to a nominal a priori initial guess

in order to obtain the real value of p:

$$p = p_{nom} + \Delta p \qquad (1)$$

The real system behaves according to

$$\dot{x} = f(x, p, d) \qquad (2)$$

where x is the state vector (pitch, pitch rate, heave, heave rate, air pressure), p is a parametric vector to be estimated and d is a radom disturbance vector (driving noise, a sample from a stochastic ensemble).

The general case should also allow for control inputs. Let $x_{ref}$ be defined by

$$\dot{x}_{ref} = f(x_{ref}, p_{nom}, 0) \qquad (3)$$

$$x = x_{ref} + \Delta x \qquad (4)$$

where $p_{nom}$ is the "nominal" or a priori value of the parameters to be estimated. $x_{ref}$, the solution to Eq (3), differs from x, the solution to Eq (2), because of the driving noise d, and because the real value of the parameter vector p in Eq (2) differs by $\Delta p$ from the nominal value in Eq (3). The method consists of finding $\Delta p$, despite a noisy d, given an incomplete and noisy measurement vector.

Avoiding the mathematics in the limited space of this appendix, the operation of the Kalman filter used for estimation can be summarized as follows (this is an abbreviation of the rigorous method of "smoothing" developed at MIT Draper Laboratory, i.e., the use of all data, off-line, to estimate value at all times, which normally requires two Kalman filters, one filtering forward in time, and another filtering backward in time). (See Reference [3] ).

STEP 1    Propagate, for every $\Delta t$, the dynamical systems equations on a computer, ignoring the unknown driving noise, from initial conditions. Unknown initial conditions may be assumed zero. The solutions are referred to as $\hat{x}$, $\Delta \hat{x}$, $\Delta \hat{p}$, most probable or "expected value" of x, $\Delta x$, $\Delta p$.

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STEP 2        Simultaneously propagate for every $\Delta t$, the $n(n+1)/2$
              independent first order equations of the covariance
              matrix associated with the $\delta x$'s and $\delta p$'s from assumed
              initial conditions (the covariance matrix is usually
              assumed diagonal).

STEP 3        For every discrete measurement at time $t_i$:

              a.   Calculate a Kalman Gain $K_i$ from the covariance
                   matrix and a priori statistics of the driving noise.

              b.   Using the Kalman Gain, update the expected values
                   $x, \Delta \hat{x}, \Delta \hat{p}$ to account for the measurement.

              c.   Using the Kalman Gain, update the covariance
                   matrix to account for measurement.

STEP 4        Repeat Steps 1 through 3 (See Figure C-1).

Step 3 requires a priori statistics such as the covariances of driving and
measurement noises, for which good or reasonable guesses are available.
The solution to the coefficient estimation problem is $(p_{nom} + \lim \Delta \hat{p})$.
The diagonal terms of the covariance matrix associated with the $\Delta p$'s
estimate confidence levels to be expected from the estimates in the wide
sense for Gaussian processes.

Stochastic wave disturbances can be modelled based on known spectra
and can be accounted for by the useful technique of "colored noise".
Biases in the measurements, or off-setting forces and moments in the
equations of motion proper can also be treated as a number of additional
coefficients to be estimated, to which Kalman filtering is applicable.

If the basic system order is 5, and there are 10 parameters to estimate,
the number of first-order differential equations to propagate is

$$5 + \frac{n(n+1)}{2} = \frac{(5 + 10)(5 + 10 + 1)}{2} = 125$$

But the inverse problem computation does not have to be carried out over
long periods of time, as is necessary for the direct problem, and also
does not require the computation of sea waves in the direct problem
method. The direct and inverse problem may require the same bulk

C-4
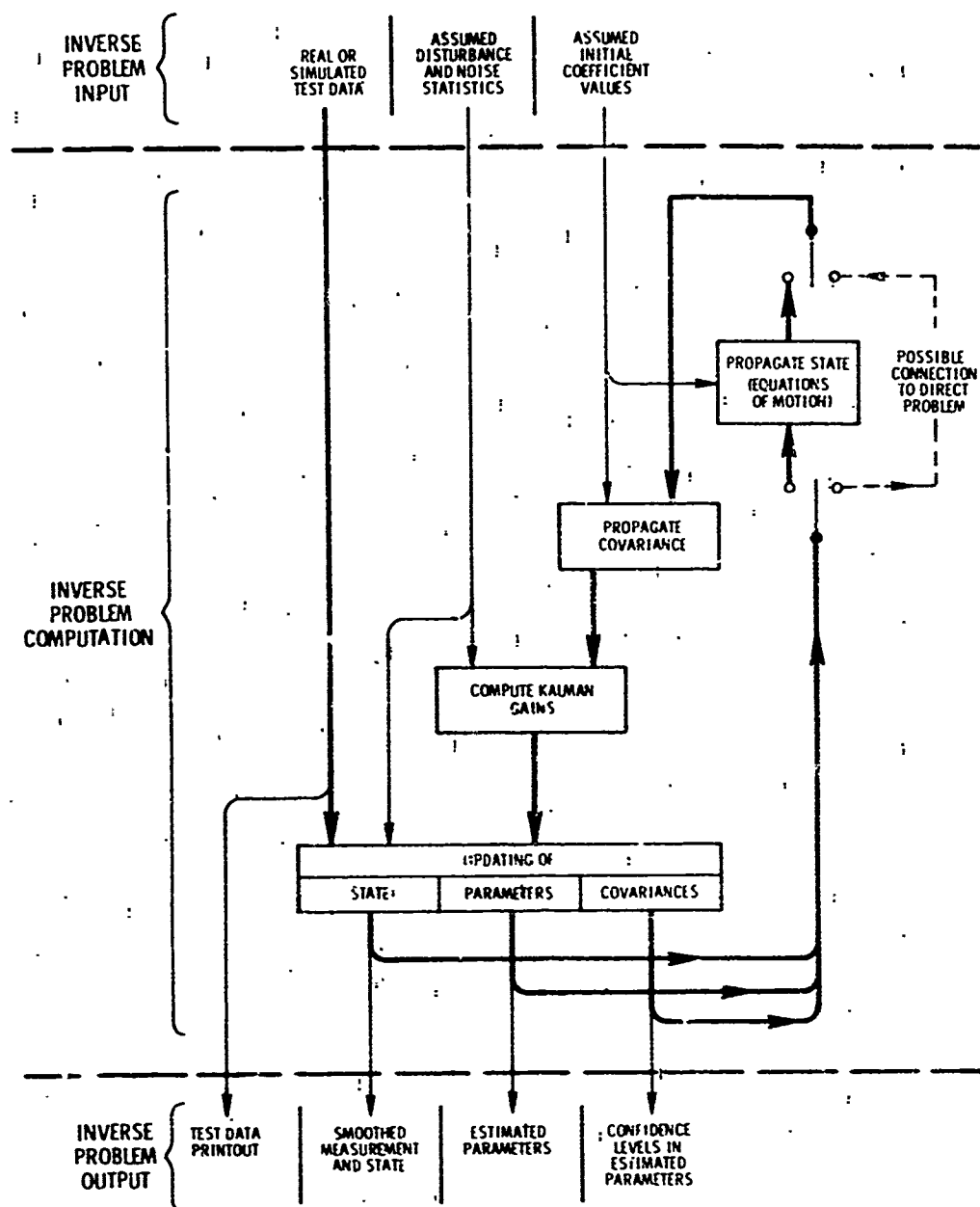
Figure C-1   Computer Flow Diagram for the
ACV Inverse Problem.

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volume of computation, because the complexity of the latter nearly off-sets the length requirements of the former. (Needless to say, the direct problem portion of the computer program, with wave excitation, will be used to simulate test data from model or full scale tests as required for the inverse problem.

However, the computer programming required for the inverse problem could be somewhat shortened. Scrutiny shows that there is no compelling reason for retaining the linear terms only of the ACV vertical plane dynamics in the solution to the inverse problem, as the identification method envisioned by MIT accommodates nonlinearities. It can be noted that the $\Delta x$ equations need not be propagated per se, and that the full-fledged equations of motion using x

$$\dot{x} = f(x, p_{nom} + \Delta p, 0) \tag{5}$$

are the same as the ones to be solved in the direct problem — where the wave disturbances are removed (note that x in Eq (5) is not the x in Eq (3) because of p). Thus, there is the interesting possibility of <u>not</u> <u>segregating the computer simulation required for the inverse ACV problem</u> <u>from the one needed for the direct ACV problem</u>. The computer program can easily remove wave excitation (or driving noise in the case that wave excitations are modelled by "colored noise") from the direct problem and solve the inverse problem by adding one more subroutine to the main program. See Figure C-1.


C.3    Input Signals for Identification

The test data available for solving the ACV inverse problem should contain both of the following types : ACV motion under the influence of initial conditions (heave, pitch, etc.) and ACV motion under the impact of open-loop control to the effectors, i.e., the rudder, etc.


C.4    Parameter Likelihood Function Model

There are other ways of using Kalman filters for systems identification. The parameter likelihood function method [8, 9] is worth investigating for the ACV inverse problem because it has the advantage of also estimating the driving and measurement noise statistics, especially if the original

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estimates are coarse. After all, this information is also imbedded in the test measurements, and an algorithm can be created to isolate this information[6].

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# APPENDIX D

## FACTS ON ANALOG AND DIGITAL COMPUTERS
## FOR A NAVAL SIMULATION FACILITY

D.1    Analog Computer Considerations for a Naval Simulation Facility

D.1.1    Selection of Analog Computer Candidates

Four computers have been retained that are worthy of consideration: the AD-4, the EAI 7800. the EAI 680, the SS-100. It was found that the specifications for these computes (noise, integrator drift, bandwidth, open-loop gain, etc.) are all adequate for a hybrid facility. Therefore, the major points of consideration between these computers should be made based on equipment complement, ability to service the prospective site, and cost. Table D-1 tabulates the maximum equipment complement for each computer (only those components that MIT deems to be desirable at this time). An inspection of Table D-1 shows that the four computers have marked dissimilarities in their fully expanded equipment complements .

In order to compare systems of equivalent size a configuration was selected such that (but for a few exceptions) each computer could be configured to within a few percent of that configuration. Table D-2 contains the nominal configuration, the configuraion for each computer and cost. Expansion of all of the computers involves simple plug-in of the desired modules since the basic console is wired for the full equipment complement. However, in many cases to expand, one must purchase modules increments as available from the vendor which may force one to obtain equipment not actually needed. For example, if one required the addition of an electronic switch for the EAI 680 one must purchase a module that contains an electronic switch, a comparator, a function relay, and an inverter.

In order to obtain one number to represent a cost index for each machine,

an arbitrary user weighting factor was applied to the maximum equipment complement of each computer. Examination of Tables D1-D3 demonstrates that

- The 10 volt EAI 680 is not significantly lower in cost than its 100 volt competitors.

- For the nominal configuration the AD-4 is the lowest cost computer (although it did not have quite as many elements as its competitors).

- A fully expanded AD-4 is the most expensive computer of those investigated, however, at its full expansion it contains many more integrators and servo set potentiometers.

- Of the three 100 volt computers the SS-100 is the most expensive.

As a result of the MIT evaluation it was made apparent that a significant savings in cost would not be realized by going to a 10 volt analog computer system (EAI 680) and since the amplitude dynamics range for a 10 volt computer is lower than for the others, the 680 was dropped from further consideration. The computers that remained in the final evaluations were the AD-4, EAI 7800 and the Hybrid Systems SS-100.

It was decided that a field trip to users of the equipment under investigation or to the manufacturers' facilities was unwarranted. Instead, in order to gain further insight into the performance and reliability of the three mentioned analog computers, MIT contacted several users of each analog computer system (AD-4, EAI 7800, SS-100).

D.1.1.1   User Comments on the AD-4 (Applied Dynamics)

The overall comments from users of the AD-4 were favorable. The users contacted have typically had their systems for two to three years. Problems were experienced with the earlier versions of the AD-4. These problems were in two areas:

1. The contacts assoicated with the printed circuit boards for operational amplifiers had connection problems. This problem was cleared up by application of a gold plating to these contacts.

2. Reed-relays associated with the moding of individual components within the Analog Computer System had a tendency to malfunction. This problem was resolved by replacing the problem relays.

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TABLE D-1

ANALOG COMPUTER EVALUATION
(MAXIMUM EQUIPMENT COMPLEMENT)

| Description | EAI 680 | EAI 7800 | Hybrid Systems SS-100 | Applied Dynamics AD-4 |
|---|---|---|---|---|
| Integrators | 30 | 42 | 42 | 64 |
| Summer Ampl. | 24 | 66 | 56 | 48 |
| Inverters (Free) | 134 | 158 | 118 | 112 |
| Multipliers | 24 | 36 | 24 | 24 |
| Sin/Cos Resolv. | 12 | 12 | 4 | 24 |
| Servo Set Pots | 120 | 144 | 160 | 256 |
| Manual Pots | 12 | 12 | 12 | 16 |
| DEG's | 18 | 24 | 12 | 16 |
| Limiters | 24 | 24 | 10 | 32 |
| Comparitors | 24 | 36 | 20 | 32 |
| D/A Switches | 24 | 36 | 22 | 32 |
| Function Switches | 24 | 24 | 24 | 24 |
| Logic | | | | |
| Flip/Flops | 36 | 36 | 8 | 16 |
| And Gates | 30 | 56 | 50 | 96 |
| One-Shots | 6 | 6 | 8 | 6 |
| BCD Counters | 3 | 6 | 0 | 12 |
| Total System Cost (Dollars) | 232,279 | 372,184 | 347,325 | 414,132 |

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## TABLE D-2

### ANALOG COMPUTER EVALUATION
### (PARTIALLY EXPANDED COMPLEMENTS)

| Description | Nominal Configu- ration | EAI 680 | EAI 7800 | SS-100 | AD-4 |
|---|---|---|---|---|---|
| Integrators | 30 | 30 | 30 | 30 | 28 |
| Summer Ampl. | 30 | 24 | 30 | 30 | 22 |
| Inverters (Free) | 55 | 60 | 52 | 56 | 50 |
| Multipliers | 12 | 12 | 12 | 12 | 12 |
| Sin/Cos Resolv. | 4 | 4 | 4 | 4 | 4 |
| Servo Set Pots | 120 | 120 | 120 | 120 | 112 |
| Manual Pots | 12 | 12 | 12 | 12 | 12 |
| DFG's | 10 | 10 | 10 | 10 | 8 |
| Limiters | 10 | 24 | 12 | 10 | 14 |
| Comparators | 20 | 20 | 20 | 20 | 20 |
| D/A Switches | 10 | 20 | 20 | 10 | 14 |
| Function Switches | 24 | 24 | 24 | 24 | 24 |
| Noise Generator | 1 | 1 | 1 | 1 | 1 |
| Patchboards | 5 | 5 | 5 | 5 | 4 |
| 8 Channel Recorders | 2 | 2 | 2 | 2 | 2 |
| X - Y Plotter 11" x 17" | 1 | 1 | 1 | 1 | 1 |
| Logic System | Maximum Available ⟶ | | | | |
| Total Cost ($) | | 207,335 | 249,745 | 254,717 | 205,890 |

## TABLE D-3

### ANALOG COMPUTER EVALUATION
### (UWF x MAXIMUM EQUIPMENT COMPLEMENT)

| Description | User Weighing Factor (UWF) | EAI 680 | EAI 7800 | Hybrid System SS-100 | Applied Dynamics AD-4 |
|---|---|---|---|---|---|
| Integrators | 1.0 | 30.0 | 42.0 | 42.0 | 64.0 |
| Summer Ampl. | 0.9 | 21.6 | 59.4 | 50.4 | 43.2 |
| Inverters (Free) | 0.7 | 93.8 | 110.6 | 82.6 | 78.4 |
| Multipliers | 1.0 | 24.0 | 36.0 | 24.0 | 24.0 |
| Sin/Cos Resolv. | 1.0 | 12.0 | 12.0 | 4.0 | 24.0 |
| Servo Set Pots | 0.25 | 30.0 | 36.0 | 40.0 | 64.0 |
| Manual Pots | 0.25 | 3.0 | 3.0 | 3.0 | 4.0 |
| DFG's | 0.5 | 9.0 | 12.0 | 6.0 | 8.0 |
| Limiters | 0.5 | 12.0 | 12.0 | 5.0 | 16.0 |
| Comparitors | 1.0 | 24.0 | 36.0 | 20.0 | 32.0 |
| D/A Switches | 0.6 | 24.0 | 36.0 | 22.0 | 32.0 |
| Function Switches | 0.1 | 2.4 | 2.4 | 2.4 | 2.4 |
| Logic | | | | | |
| Flip/Flops | 1.0 | 36.0 | 36.0 | 8.0 | 16.0 |
| And Gates | 0.8 | 24.0 | 44.8 | 40.0 | 76.8 |
| One-Shots | 1.0 | 6.0 | 6.0 | 8.0 | 6.0 |
| BCD Counters | 1.0 | 3.0 | 6.0 | -6.0[*] | 12.0 |
| Sum of UWF x (Max Comp) | | 354.8 | 490.2 | 351.4 | 512.8 |
| Total Price | | $232,279 | $372,184 | $347,325 | $414,132 |
| $\frac{Cost}{Benefit} = \frac{Total\ Price}{Sum\ of\ UWF\ x\ (max\ compl)}$ | | $654.68 | $759.25 | $988.40 | $807.59 |

[*]Since none were available, a penalty was imposed.

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It was also learned from several users that ADI handled the interface system to their digital computer. The results of this task undertaken by ADI were satisfactory in terms of noise level accuracy and reliability.

All users contacted were quite impressed by both the accuracy and bandwidth of the system[*].

The large frequency bandwidth was found advantageous in repetitive-operation (REP-OP). But it is felt that the REP-OP capability will be of little value to the ACV simulation.

The nonlinear component accuracy was judged to be outstanding by one of the users. He found that this afforded him a nonlinear problem-solving capability that he had not expected. (This user was a strictly analog user and not a hybrid user.)

The patchable logic system was satisfactory with no major problem encountered by any of the users contacted.

The overall response from the users was that they were satisfied with the AD-4 system and that they would obtain the AD-4 again if further analog capability was required.

D.1.1.2  Users' Comments on the EAI 7800 (Electronics Associates, Inc.)

As in the case of the AD-4 user, the users of the EAI 7800 system were quite satisfied. In the case of the 7800 users, there is a marked tendency to stay with EAI. Several of the users contacted had older EAI equipment (EAI 231R's, TR 48's). Their satisfaction with this older equipment led them to continue to purchase EAI equipment.

No specific complaints or problems were given by the users of the EAI 7800.

D.1.1.3  User Comments on the SS-100 (Hybrid System)

The SS-100 Analog Computer seems to have been purchased mainly in the southwest area of the country. One of the users contacted (KIN-O-

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[*]  In one case the user commented that the high bandwidth of the system made it sensitive to externally generated noise. This user said he had to take precautions with certain problems when patched on the analog computer to maximize noise rejection. Often the type of problem that will generate or amplify noise can be placed on the digital portion of a hybrid facility, e.g., divide circuits, comparator circuits, etc.

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TROL) gave fairly strong comments as to the superior computing power and specifications of the SS-100 system as compared to EAI 7800 or ADI AD-4. It is believed that this company is a consultant to Hybrid Systems, and so their comments should be put in perspective.

Overall the response from other users contacted indicated satisfaction with the SS-100.

### D.1.1.4 Summary of User Comments on Candidate Analog Computers

Overall the three analog systems considered by MIT all have essentially the same customer rating (good to very good). No insurmountable problems were encountered by users of the three computers. There seems to be a definite tendency for the user of a particular analog computer customer to stay with the same manufacturer over the years.

### D.2 Digital Computer Consideration for a Naval Simulation Facility

### D.2.1 Comparison of Computer Candidates

Table D-4 is a snapshot summary of the characteristics of the eight computers investigated. Items that are not self-explanatory include:

Item 13 : "Short Fixed Point Subroutine" ($\mu$sec) lists the time required to perform a short subroutine that was coded in assembly language using fixed point math. This time was obtained by adding the time to execute each instruction without interleaving memory (if available).

Item 14 : Same as Item 13 except using floating point math.

Item 15 : "Interrupt Response Time" is the time to recognize an interrupt (hardware time), save all registers, execute an operation, restore all registers, clear the interrupt and return to the interrupted location plus the time to execute a floating point multiply.

A few general remarks are in order regarding Table D-4. The instruction execution times quoted were obtained from vendors or their manuals. Where ranges of time, i.e., maximum and minimum were given, these times were averaged. Consequently, small discrepancies may exist in comparing vendors' instruction execution times, as in some cases one may be comparing an average time of one vendor with the minimum time

## TABLE D-4

## COMPUTER SPECIFICATIONS

| | SEL 8600 | DEC PDP-10 | Honey-well H632 | XDS Σ5 | IBM 360-44 | CDC 3600 | XDS Σ8 | CDC 3800 |
|---|---|---|---|---|---|---|---|---|
| 1. Basic Memory Cycle Time (μsec) | 0.6 | 1.0 | 0.85 | 0.85 | 1.0 | 1.5 | 0.85 | 0.9 |
| 2. Word Length (Bits) | 32 | 36 | 32 | 32 | 32 | 48 | 32 | 48 |
| 3. Maximum Core Size (1024 Words) | 128 | 256 | 128 | 128 | 96 | 256 | 128 | 256 |
| 4. Increments of Core (1024 Words) | 8 | 16 | 8 | 8 | 32 | 32 | 16 | 32 |
| 5. Number of General Purpose Registers | 8 | 16 | 16 | 16 | 16 | 2 | 16 | 2 |
| 6. Number of Index Registers | 3 | 15 | 7 | 7 | 16 | 6 | 7 | 6 |
| 7. Interleaving of Memory | No | Yes | Yes | Yes | No | Yes | Yes | Yes |
| 8. Ports to Memory (Maximum) | 4 | 4 | 8 | 6 | 4 | 5 | 12 | 6 |
| 9. Fix Point Add (μsec) | 1.2 | 2.53 | 1.7 | 2.9 | 2.25 | 2.07 | 0.73 | 1.5 |
| 10. Floating Point Add (Short) (μsec) | 3.6 | 4.46 | 9.35 | 7.2 | 4.56 | 4.25 | 3.69 | 3.13 |
| 11. Fix Point Multiply (μsec) | 6.0 | 10.6 | 9.35 | 8.2 | 16.89 | 6.70 | 3.32 | 5.63 |
| 12. Floating Point Multiply (Short) (μsec) | 6.6 | 10.29 | 13.6 | 10.7 | 62.64 | 6.40 | 4.72 | 5.80 |
| 13. Short Fixed Point Subroutine (μsec) | 31.2 | 58.0 | 47.6 | 51.8 | 75.7 | 42.3 | 26.3 | 33.0 |
| 14. Short Floating Point Subroutine (μsec) | 45.0 | 66.7 | 98.6 | 80.8 | 224.5 | 52.3 | 38.0 | 41.9 |
| 15. Interrupt Response Time (μsec) | 20.4 | 89.4 | 88.6 | 4?.7 | 129.9 | 76.7 | 34.7 | 47.6 |
| 16. Priority Interrupt Structure | Excel-lent | Good | Good | Excel-lent | Fair/Good | Fair/Good | Excel-lent | Fair/Good |
| Cost (Kilodollars) | 550 | 583 | 587 | 595 | 624 | 674 | 682 | 791 |

\* Prices quoted were either GSA or list price (see discussion later).

\*\* DEC estimates that the additional cost of a KI-10 Processor instead of a KA-10 Processor will be from 100 to 140 K. Therefore, a PDP-10I should cost from 683 to 723 kilo dollars.

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of another. However, since the range of execution time is not generally very broad no attempt was made to contact vendors to resubmit information.

D.2.2    Reduction of Number of Candidates to only Three Candidates

Table D-5 orders selected characteristics of Table D-4. It should be kept in mind that interleaving of memory would reduce the instruction execution times of Table D-5 for all vendors except for the SEL 8600 (which is a synchronous computer) by anywhere from 5 to 30%. At this point it was decided to judicially reduce the number of computers under consideration, and Tables D-4 and D-5 are useful to accomplish this goal:

> From Table D-5 one observes that the IBM 360-44 has the longest response times of the computers under consideration. There are very significant differences in execution time between this computer and all others considered, and since computer speed is of considerable importance the 360-44 was dropped from further consideration.

> The CDC 3600 and 3800 computers are reconditioned versions of computers no longer in production and they are at the top of the list in cost. Consequently, software support is extremely questionable and assembly language programming would be severely limited by the availability of only the two general purpose registers. Since other computers in the list do not have these severe limitations the CDC 3600 and 3800 were dropped from further consideration.

> The Honeywell H-632 computer is near the bottom of the list in speed of operation and due to organization difficulties at this period of time, as well as other unspecified contingencies it was decided to drop the H-632 from further consideration.

> The XDS Sigma 5 digital computer instruction execution times are approximately twice as long as the XDS execution times for the newly announced XDS Sigma 8. In view of the fact that the Sigma 8 software is fully compatible with the software developed for the Sigma 5, and that the price difference be-

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TABLE D-5

HARDWARE COMPARISON TABLE

| | INTERRUPT RESPONSE TIME | | FIXED POINT SUBROUTINE TIME | | FLOATING POINT SUBROUTINE TIME | | SUM OF INTERRUPT FIXED, FLOATING SUB. | |
|---|---|---|---|---|---|---|---|---|
| | VENDOR | TIME ($\mu$s) | VENDOR | TIME ($\mu$s) | VENDOR | TIME ($\mu$s) | VENDOR | TIME ($\mu$s) |
| 1 | SEL 8600 | 20.4 | XDS Σ8 | 26.3 | XDS Σ8 | 38.0 | SEL 8600 | 96.6 |
| 2 | XDS Σ8 | 34.7 | SEL 8600 | 31.2 | CDC 3800 | 42.0 | XDS Σ8 | 99.0 |
| 3 | XDS Σ5 | 42.7 | CDC 3800 | 33.0 | SEL 8600 | 45.0 | CDC 3800 | 122.6 |
| 4 | CDC 3800 | 47.6 | CDC 3600 | 42.3 | CDC 3600 | 52.3 | CDC 3600 | 171.3 |
| 5 | CDC 3600 | 76.7 | H-632 | 47.6 | PDP-10 | 66.7 | XDS Σ5 | 175.3 |
| 6 | H-632 | 88.6 | XDS Σ5 | 51.8 | XDS Σ5 | 80.8 | PDP-10 | 214.1 |
| 7 | PDP-10 | 89.4 | PDP-10 | 58.0 | H-632 | 98.6 | H-632 | 234.8 |
| 8 | 360-44 | 129.9 | 360-44 | 75.7 | 360-44 | 224.5 | 360-44 | 430.1 |

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tween a Sigma 8 and a Sigma 5 is less than $100,000, the Sigma 5 was eliminated from further consideration.

The PDP-10 is near the bottom of the list in speed of operation. However, an updated version of the PDP-10, for reference called the PDP-10I, is expected to be announced shortly. Tentatively; this computer could be delivered in the Fall of 1972 and represents an upgrading of the PDP-10, which will be from two to three times faster than the PDP-10. Since the reputation of DEC is excellent, and the PDP-10 reasonably competitive as is, it was decided to allow the PDP-10 to remain in the competition assuming the DEC would be willing to bid a PDP-10I with delivery of a PDP-10, to be replaced by a 10I when available. Since it is unlikely that time critical problems will be operating prior to estimated 10I deliveries, this approach seems reasonable.

Therefore, the list of computers still in contention at this point are:

The SEL 8600

The XDS Sigma 8

The PDP-10I

A word of caution. The terms "fastest" computer, "slowest" computer or similar expressions can be bandied around rather loosely. It is highly likely that for one special problem each vendor can show that he can execute that problem faster, or compile that problem faster than its competition, thereby claiming he has the "fastest" computer. The simple tables are not intended to demonstrate general superiority or speed of any one computer, but rather are intended to be used in conjunction with other considerations. Thus, although the CDC 3800 is a fast powerful computer, it seems unwise to pay the highest price for it when it does not demonstrate obvious superiority over its competition and has severe limitations in other areas as already stated. The five computers dropped from consideration are not poor performers; there merely are other computers that at th⸱ time represent better values at lower risks for a hybrid facility to simulate Air Cushion Vehicles and other Navy crafts.

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Both the XDS Sigma 5 and the DEC PDP-10 computers are presently in use in hybrid facilities. Both vendors have tentatively scheduled or planned release of newer, compatible computers, the XDS Sigma 8 and the DEC PDP-10I. The XDS Sigma 8 is scheduled for release at the end of this year, the PDP-10I in the fall of 1972. Due to the significant increase in computer speed both these computers offer as oppoed to their "stablemates" at a modest increase in cost, the newer computers are more cost-effective for a Naval Simulation Facility. However, some length of time will elapse until the speed differences in the newer computers will actually be required. Therefore, should XDS propose a Sigma 5 as an interim computer until Sigma 8 delivery, and/or DEC propose a PDP-10 as an interim computer until PDP-10I delivery, such proposal(s) should be viewed favorably.

A survey was made of users of the SEL 8600, XDS Sigma 5 and DEC PDP-10. Before discussing that survey a brief description of each computer and computer company is in order.

The following information has been extracted from the vendors 'esponse to the RFI or his sales literature. Claims made in the next sections are the manufacturer's claims and should be so viewed.

D.2.3    Facts Summary of Systems Engineering Laboratory and the SEL 8600

Systems Engineering Laboratory (SEL) began in 1961 by developing custom data measurement systems for use with computers. As a natural out-growth SEL began developing 16-, 24- and 32-bit real-time computers. In 1969 SEL announced their 32-bit SEL 8600 computer system and began deliverieis of this system in 1970. Their real-time computer systems are at work in industry, government, education, medicine and research.

D.2.3.1    The SEL 8600 Computer

The SEL 8600 is a totally integrated hardware-software computer system designed specifically for real-time operations. It is being used in various real-time applications.

A summary of the specifications and capabilities of the SEL 8600 System follows:

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## Central Processor Unit

- Priority Interrupt System — Containing up to 128 interrupt levels. Interrupt priority scheduling is fully automatic. Individual interrupt levels can also be enabled, disabled, requested, activated, and deactivated all under program control.

- Real-Time Interrupt Response — Interrupt response time ranges from 0.6 micro-seconds to 6.6 micro-seconds worst case.

- Masking Capabilities — Masking can be performed as part of the execution of register-to-register, arithmetic and logical instructions. No additional instruction execution time is required for masking.

- User-Oriented Programming Systems — Exploits the System's 86-nanosecond instruction execution speed for foreground processing while giving the user background processing capabilities with minimum system overhead.

- Mode Keyswitch — Allows the user to command the degree of control that the currently active program has over system resources.

- System Protect Hardware — Guarantees instantaneous core storage of the current system status in the event of power failure, and automatic program recovery when power is restored.

- System Protect Keyswitch — Allows the user to selectively lock out intervention from the control panel, the system over-ride interrupt, and auto start interrupt. The user determines the degree of program interference that can be exerted by external sources.

- Register Imaging — Execution of one instruction, loads or stores the content of all eight general-purpose registers in only 5.4 microseconds. General-purpose registers assume a true multi-task role.

- Transfer of Data Between Registers — Execution of any register-to-register instruction takes only 600 nanoseconds.

- Memory Utilization — Over 30 percent of instructions are half-word instructions and can be packed two per memory location.

- Halfword Addressing — Enables accessing and operating on 16-bit operands packed two per memory location without any reformatting time penalties.

- Variable Precision Arithmetic — Fixed-point instruction set permits arithmetic operations to be performed on quantities of data ranging from a byte (8 bits) to a doubleword (64 bits). Add and subtract in byte, halfword, word, and doubleword data lengths. Multiply and divide in byte, halfword and word data lengths.

- Direct Addressing of Entire Core Memory — Any bit, byte, half-word, word or doubleword in up to 128 K of memory is directly addressable.

- Indexing — Can be selected according to the exact needs of the problem. Positive and negative indexing quantities can range from a byte to the entire memory capacity in increments of bytes, half-words, words or doublewords.

- Pre and Post Indexing — At no "over-head" cost in time.

- Multilevel Indirect Addressing — Indirect addressing can go to any depth. Users can keep data sections of programs separate from procedures section for ease of use.

- Real-Time Clock — Provides an accurate reference for program sequencing; times real-time functions to occur at specific instants; measures elapsed time, time of day, etc.

- Floating-Point Arithmetic Hardware — Floating-point arithmetic instruction set contains single-word formats for storage economy, and doubleword formats for increased resolution and fractional significance.

- Floating-Point Guard Digit — Enables the least significant bit to be rounded automatically after all arithmetic operations.

- Arithmetic Exception Interrupt — Provides automatic hardware detection of overflow after every arithmetic operation; eliminates ⁺ ⁱⁿ consuming testing of overflow and underflow.


## Memory

- Memory Cycle — Full read/selective-replace/restore memory cycle time of only 600 nanoseconds - the fastest memory cycle offered by any comparable computer.

- Memory Byte Parity — A parity bit stored with each 8-bit byte permits selective replacement of individual bytes with no added time penalty.

- Word Slicing — Permits reading and writing of individual bytes or halfwords in any memory location.

- Modularly Expandable Core Memory — Standard 8 K core memory modules make it easy and economical to expand memory from a basic 8 K (8192 32-bit words) up to 128 K (131, 072 32-bit words).

- Total Protection of Vital Information Stored in Memory — Power fail-safe feature prevents modification of memory data, either in the event of power failure or during normal turn-on and turn-off.

- Multiple Memory Ports — Memory accesses for both input/output program execution can be performed during the same memory cycle.

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- Direct Memory Access — Provides an input/output path that completely by-passes the central processor; transfers data on a non-cycle stealing basis at maximum rates.

- Memory Page Protect — Gives the user program control over access to selectable pages of memory. Areas of memory can be kept private for individual user's programs. Foreground and background programs can be run concurrently. Foreground programs are protected from unchecked background programs.

### Input/Output

- Fully Automatic Input/Output System — Requires minimum central processor involvement. Peripheral device commands from central processor are executed in only 600 nanoseconds; more central-processor time is available for program execution.

- High-Speed Exchange of Input/Output Data — Data transfers occur at rates of up to 1,666,666 32-bit words per second.

- Concurrent Data Exchanges with Peripherals - Up to sixteen device controller channels perform concurrent fully buffered data transfers in either a single-word or high-speed block-transfer mode. Each device controller channel interfaces with either a single peripheral device or a multi-peripheral device controller.

- Automatic Reinitialization of Block Transfers — Enables continuous transfers from non-contiguous areas of memory. Each block transfer can be programmed to start automatically at the completion of the preceding block transfer.

- Variable Width Data Exchange Paths — Input/output data can be formatted in byte, halfword, or word increments.

- Program Transparent Priority Scheduling — Of device controller channels allows the system to be reconfigured, expanded, and tuned to specific needs without altering the software. Device controller channels can be interchanged without changing the virtual priority levels used in the interrupt control instructions because all parameters which effect programming are hardware implemented within the device controller channels.

- High- and Low-Priority Device Controller Channels — For maximum data handling efficiency when operating with both fast and slow responding peripheral devices.

D.2.3.2   SEL 8600 — Software

SEL has two monitor systems for the SEL 8600, BPS (Batch Processing System) and RTM (Real-Time Monitor) The Real-Time Monitor is the monitor that would be used in a hybrid environment. It is a disc-oriented multi-programming system that supports real-time and batch processing for a variety of applications and hardware configurations.

Included in the standard features of RTM are the following:

- Multiprogramming environment supporting concurrent execution of 64 programs.

- 64 priority levels for multi-level operation.

- Interrupt and trap processing for all interrupt and trap levels.

- Timer scheduling of foreground and background programs.

- System security via dynamic memory protection feature.

- Spooling concurrent Input/Output using system disc.

- Re-entrant monitor services available to both foreground and background programs.

- On-line cateloging of foreground and background programs.

- Dynamic assignment of foreground and permanent file allocation.

- File management - temporary and permanent file allocation.

- Automatic checkpoint of background area when required.

- On-line system control from the console keyboard/printer.

- Program debugging features including dump, snapshot, and trace.

- Program overlays.

- Batch job processing through a job control language.

- System generation with hardware configuration options.


RTM is logically divided into three parts: System Modules, System Processor and the System Subroutine Library.

1.  System Module - is a collection of related but independent functions conveniently grouped under module name.

2.  System Processor - The system software processors are non-resident and are activated via specific job control statements. They include

    a.  System 86 FORTRAN IV Computer
    b.  Assembler
    c.  Marco Assembler
    d.  File Manager
    e.  Text Editor
    f.  System Generator

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g.  Debug Processor

3.  System Subroutine Library  —  The System Subroutine Library
    consists of FORTRAN I/O interface subroutines, mathematical
    subroutines, etc.

D.2.4    Facts Summary on Xerox Data Systems and the XDS Sigma 5/8

In 1961 Scientific Data Systems (SDS) was founded, and in 1962 marketed
their first "9" Series computer, the SDS 910 which was the first silicon
transistor computer commercially available.  In the periods of 1963 to
1965, SDS introduced the 920, 9300, 930 and 925 computers.  In 1965
they announced the first Integrated Circuit Computer, the 12 bit SDS 92.

Up until this period of time they were a custom real-time house.  In the
spring of 1966 SDS announced the first two computers of the Sigma line,
the Sigma 2 and the Sigma 7, and the following year delivered the first
Sigma 5.

The Xerox Corporation bought out SDS in 1969 and Scientific Data Systems
(SDS) became Xerox Data Systems (XDS).  The Sigma 9, a further up-
grade of the Sigma 7 was announced in 1970.  First delivery of the Sigma
9 is expected in the fall of 1971.  This spring XDS announced the Sigma
8, an upgrade of the Sigma 5/Sigma 7 with the same memory as the
Sigma 9.  Deliveries are expected to begin at the end of this year.  XDS
has had a long and successful history in the scientific market.

D.2.4.1  XDS Sigma 5 Computer

The Sigma 5 has been developed for four general categories of computa-
tion.  The four areas are

1.  General-Purpose Computing

2.  Real-time System Control

3.  Time-Sharing

4.  Multi-Use Computing

In the area of real-time applications, the need for high speed and an
instantaneous response to an external environment is required.  Also
required is sufficient input/output flexibility to handle many types of
data and an efficient programming system to reduce programming costs.
The Sigma 5 has a series of features (such as the priority interrupt sys-
tem and the Real-time Batch Monitor (RBM)  software system)  that

provides an effective real-time capability.

## General Characteristics

The particular features and characteristics that enable Sigma 5 to operate efficiently in real-time, general-purpose, and multi-use applications are summarized below.

- Sigma 5 has an 850 nanosecond memory cycle time; the effective cycle time can be further reduced by using over-lapped memories operating asynchronously.

- Sigma 5 has a word-oriented memory (32 bits plus parity) for maximum efficiency, as well as data compatibility with IBM System/360 and modern communication codes such as EBCDIC or ASCII. Memory is addressable and alterable by byte (8 bits), halfword, word and doubleword.

- The memory capability is from a minimum of 8,192 to 131,072 words, in 8,192-word increments.

- The entire memory can be addressed directly, without the need for base registers.

- Indirect addressing can be used, with or without indexing, for additional programming power.

- 16 general-purpose registers are included (expanisble to 256 registers).

- Displacement index registers automatically adjust for data size, resulting in simplified programming and more effective use of index registers.

- Sigma 5 incorporates full parity checking of memory and input/output transmission.

- The complete instructions set includes byte, halfword, word, and doubleword operations. Fixed-point arithmetic operations are handled in halfword, word, and doubleword modes; optional floating-point hardware operates in both short and long formats.

- Complete memory write protection guarantees data integrity.

- The real-time priority interrupt system features up to 224 interrupt levels with automatic hardware identification, priority control, and extremely fast response time.

- Up to four real-time clocks are available, each with independent choice of time base (two are standard).

- For operation protection, the system has priviledged instruction logic (Master/Slave modes).

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- The self-organizing input/output system includes both data and command chaining for powerful input/output capability. Eight fully automatic input/output channels are standard (expansible to 32) on the Model 8201 CPU. The Model 8202 CPU does not have, as standard, an integrated IOP but uses an external IOP. Up to eight input/output processors may be used for expanded I/O capacity; also available is a feature for direct input/output of a full 32-bit word without the use of an automatic channel.

- Sigma 5 is completely upward-compatible with the larger and more versatile Sigma 7. This means that the growth of a system's computing capability can be based on real, present requirements. Sigma computers can be combined in multi-processor configurations to suit varying requirements.

- XDS software expands in capability and speed as a system grows, with no reprogramming required.

- Basic Control Monitor permits concurrent background/foreground operations.

- Real-time Batch Monitor permits background/foreground operations and sequential batch operations with an emphasis on real-time operations.

- Batch Processing Monitor increases system capabilities by including background/foreground operations, concurrent peripheral I/O operations (symbionts), remote batch operations, and priority scheduled batch operations.

- Batch Time-Sharing Monitor permits priority scheduled batch operations, remote batch, symbionts, and a maximum of 38 simultaneous conversational time-sharing users.

- FORTRAN IV compilers include IV-H for smaller configurations, XDS FORTRAN IV for expanded capability, and a high-efficiency version for faster object program execution.

- Efficient Symbol assembler gives maximum power for smaller configurations; larger systems can use Macro-Symbol or Metro-Symbol, which have expanded capability, and real-time features.

- Business package includes optional XDS COBOL 65, a Sort/Merge package that uses the XDX RAD for increased proccessing speed, and a 1401 Simulator.

- An optional Linear Programming Package (Sigma FMPS) and a simulation language (SL-1) are available to aid in deciding programs that confront business, science and industry every day.

- Comprehensive system library provides more than 150 utility and mathematical programs. In addition, the XDS Users' Group library includes a wide variety of applications-oriented software and a numerical subroutine package.

- Standard XDS system interface units permit a wide range analog and digital devices to be connected to a Sigma 5, without special engineering costs.

D.2.4 2  XDS Sigma 8 Computer

The XDS Sigma 8 computer design is compatible with the Sigma 5 computer
design, representing an enhancement of the salient features of the Sigma 5.
All of the software that has been developed for the Sigma 5 is upward
compatible for the Sigma 8.

D.2.4.3  XDS Software

XDS has three monitors that are applicable to the Naval Simulation Facility.
The three are BPM (Batch Processing Monitor), BTM (Batch Time-
Sharing Monitor) and RMB (Real-Time Batch Monitoring).

RBM is of particular interest to the hybrid environment in terms of its
foreground/background capability in a real-time environment.  The
following is a list of features included in RBM:

1.  Performance of all I/O functions in queued priority
    sequence.

2.  Monitor is self overlaying.

3.  I/O functions concurrent with computation.

4.  Overlay loader provides for program segmentation.

5.  Minimal core storage.

6.  Background (non real-time) processing whenever space and
    and time permit.

7.  Operator intervention whenever required for backgrc ind.

8.  Automatic background checkpoint and restart capabilities.

9.  Rapid response to interrupts.

10.  Direct user I/O in the foreground operation.

D.2.4.4  Batch Processing Monitor

The Batch Processing Monitor enables users to exploit the capabilities
of the XDS Sigma 5 computer system more fully.  The BPM provides
maximum computing power and the flexibility normally found only on
larger, more expensive systems.

Designed within the framework of sophisticated simplicity, the monitor
can be implemented to the user's own environmental needs.  The BPM
simplifies computer utilization in a job shop environment, where maxi-
mum efficiency is required on a production basis.  In addition, the system

can accomodate real-time foreground processing on a dynamic basis.

Critical real-time tasks can be either permanently established in the operating environment or established and dismissed under operator control. Under the fundamental concept of multiusage, foreground tasks can be processed compatibly and concurrently with both a background production job stack and symbionts, thus realizing three levels of concurrent processing.

The XDS Sigma 5 Batch Processing Monitor incorporates the following features:

- Efficier⁺ and comprehensive I/O service to user programs.

- Automatic job sequencing for closed shop operations.

- Dynamic real-time process initiation and execution, concurrent with background production tasks.

- Maximum use of rapid-access secondary storage (XDS RAD files).

- Comprehensive operator control of system operation.

- Sophisticated (but easy-to-use) processor services for program creation, debugging, and execution.

- Recognition of administrative priorif ͜ssignment on incoming jobs.

- Checkpoint service.

- Automatic job accounting.

- Remote batch processing option.

- Comprehensive management of secondary storage.

- Flexible job scheuling for efficient throughput and recognition of installation priorities.

- Unimplemented instruction traps to simulate unavailable hardware options.

- Sophisticated error processing.

- Modular and flexible design for user modification.

- Overlay techniques to minimize core memory residence requirements.

- Upward compatibility with XDS Sigma 7 programs.

- Complete memory protection of the operating environment and the real-time processes.

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### D.2.4.5   Batch Time-Sharing Monitor

BTM combines the facilities of the operationally proven XDS Batch Processing Monitor and a time-sharing Terminal Executive program. Thus, the batch processing capability provided by BTM fully exploits th· computing power and versatility inherent in Sigma systems, and contains all of the features of BPM.

Designed around the concept of a balanced system, the system can be configured and tuned (parameter adjustment) to satisfy various requirements for on-line responsiveness, batch throughput, and remote batch processing. With the addition of symbiont processing for I/O, there are essentially four levels of concurrent processing.

The Sigma 5 Batch Time-Sharing monitor incorporates the following features:

- Convenient time-sharing and batch operation.
- Multiprogrammed peripheral processing (symbionts).
- Batch job entry from on-line terminals.
- Remote batch processing.
- Easy startup/shutdown of terminal operations.
- On-line responsiveness.
- High batch throughput.
- Variety of efficient on-line processors.
- Variety of powerfu· )atch processors.
- Unified file management.
- Complete account system.
- Flexible control of configuration resources (tuning)
- Complete memory protection of ·he operating environment.

### D.2.5   Facts Summary on Digital Equipment Corporation (DEC) and the PDP-10 (I)

DEC started in 1959 with the PDP-1 digital computer. At that time it started development of real-time systems for science and industry. DEC's customers have been building time-sharing systems since 1960.

In 1963, DEC developed its own time-sharing computer, the PDP-6 – the first to be delivered with manufactuer-supplied hardware and software. The PDP-10, which was built on the expertise developed from the PDP-6, reflects the DEC's experience in both real-time and time-sharing. Most of the 150 or so PDP-10 installations perform a simultaneous mix of interactive time-sharing, batch processing, and real-time operations.

D.2.5.1  DEC PDP-10 Computer

The DEC PDP-10 has been designed as a real-time, time-sharing digital computer. Some of the highlights of the PDP-10 are as follows:

- A modular system with true open-ended expandability.

- Asynchronous operation of processors, memories, and peripherals.

- 36-bit word length plus parity for both arithmetic operation and data transfers.

- 366 instruction repertoire, including floating-point, variable-length byte manipulation and half-word instructions.

- Direct memory addressing to 262,144 words.

- A multiprogramming monitor able to run real-time, batch, remote batch and timesharing simultaneously.

- Real-time jobs or tasks are capable of being "locked" into core by means of a monitor call.

- Real-time jobs or tasks may be linked to interrupt levels by means of a monitor call.

- Programs may share a common core area.

- Memory partitions are dynamic and change automatically under monitor control as required by system loading.

- All user programs are protected from accessing memory outside of an assigned memory area peculiar to their job number without specific permission (implemented by hardware).

- A dynamic scheduler positions jobs in various queues determined by the job history, current state, and other various system optimization criteria.

- Standard I/O devices can be connected to several different priority levels so that I/O is handled efficiently (software supported).

- No difference in language specifications and compilers from batch to timesharing systems.

- Programs are device independent. That is, peripherals are assignable at run time.

### D.2.5.2 DEC PDP-10 Software

The monitor system that will support both the real-time as well as the time-sharing environment is the DEC PDP-10, TOPS-10 Monitor.

DEC's TOPS-10 monitor system supports:

1. Time-sharing.
2. Batch
3. Real-time

All of the PDP-10 software is designed to run in the TOPS-10 environment. Some of the software that runs under the TOPS-10 Monitor is:

1. MARCO Assembler
2. FORTRAN IV
3. BASIC
4. TECO - Text Editor

TOPS-10 Services

1. Fast response to interrupts.
2. Core Management Control.
3. Job Priority Assignments.

The TOPS-10 Monitor Services are divided into six distinct areas:

1. The Swapper — is responsible for deciding whether a job not in core should be swapped in.

2. The Command Decoder — examines commands which appear in teletype input buffers, checks them for legality and marks the appropriate command processors.

3. The Scheduler
   a. Core Allocator
   b. Context Switcher
   c. Scheduling Algorithm

4. The UVO Handler — is the interface between user programs and the monitor.

5. The Input-Output System — allows the monitor to give each program device independence.

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6. The File Handler – it provides for permanent user storage.

Some features of the New K110 CPU

1. Over two times the KA10 speed.

2. Hardware paging.

3. Double-precision floating point arithmetic. *

4. Multiple registers.

5. Expanded interrupt structure.

6. Incorporates multi-processor systems.

D.2.6    User Comments on the Candidate Computers for a Naval Simulation
Facility

A considerable amount of reliable information can be obtained by contacting
the users of the computers under investigation. MIT has communicated
with some 50 companies and agencies scattered around the U.S. and
Canada, either through personnel interviews or mostly by telephone.
Clearly, users of equipment may sometimes have a stake in the computer
that they selected and be reluctant to indicate where they erred. However
serious and less serious shortcomings of the systems and the vendors
were freely discussed nonetheless, and a realistic picture of capabilities
was drawn.

D.2.6.1  User Comments on Systems Engineering Laboratory and the SEL 8600

The users contacted for the SEL 8600 were all using the SEL Batch
Processing System (BPS) except one who was using the Real-Time Monitor
(RTM). The BPS has been in existence about one year. The RTM has
not been formally released to SEL users. A pre-release version of RTM
has been given to one user who has only had the monitor six weeks and
therefore has not had the chance to fully exercise the software system.

The BPS Monitor at this point is quite well debugged and 8600 users were
satisfied with its performance. A few problems still exist with the BPS
but are thought to be minor in nature and should be remedied shortly.

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* Not available on the KA-10.

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The users have commented that the documentation for the software is poor but improving. SEL has recognized the present shortcomings of their documentation and have supported their software to all users' complete satisfaction. The FORTRAN software system has had a few problems but nothing of major consequence. The FORTRAN package was developed by Leasco and is currently being supported by both Leasco and SEL.

The SEL 8600 hardware, both the main frame and peripherals, have been relatively free of problems with the only exception being the card reader, which has proved to be problemsome to most of the users contacted. MIT/Draper Laboratory has been advised that a card reader, from a different source, is available and has performed well in those facilities where it has been put into operation.

Overall, the comments from the users of the SEL 8600 have been that the computer system hardware is very satisfactory and that the software is fair and improving.

The contractual concessions made to some 8600 users was the factor that persuaded those users to buy SEL. The users recognized that there were certain risks involved in selecting SEL at the time they did and SEL did whatever they could to minimize the risk and allay the users' doubts.

D.2.6.2  User Comments on Xerox Data Systems and the Sigmas

The following comments were obtained from a significant number of Sigma 5 users. Most Sigma 5 hybrid users obtained their computer systems in 1968 or 1969 and have used or are still using Real-Time Batch Monitor (RBM-1, the first real-time monitor supplied for the Sigma 5 and no longer supported by XDS. According to the users, the reason that they have not switched to RBM-2, the current Sigma real-time monitor, is that the two monitors are not totally compatible and therefore a considerable amount of work would be requi red to perform this update.

In the case of RBM-1 considerable problems were encountered by the users. The response from XDS to these problems was slow at that time (1968) but improved significantly in 1969 and 1970. In general, one common problem that users have had with XDS is that of poor support from the XDS district offices. The only way most users obtain service from the district office is to "pound on the doors" as the users say or

call XDS headquarters in California. Two of those surveyed commented that special consideration is given to large volume accounts of XDS. In general, the documentation was found to be considerably poorer than had been expected. XDS manuals were thought to be good reference manuals but poor instruction manuals.

The Sigma 5 hardware has been fairly trouble-free although problems have been experienced with some peripherals (Magnetic Tapes, Card Readers). Proper preventative maintenance seems to be difficult to obtain due to a continual turnover of field service engineers.

The Sigma software, according to the contacted users of the RBM-2 Monitor System, seems to be adequate. Users generally feel that Sigma software has improved considerably since 1968.

Several users were contacted who were using the Batch Time-Sharing Monitor (BTM). The comments from the BTM users were that the earlier versions of BTM had significant problems, but as revised versions were released problems encountered were minimal. The latest version of BTM has performed quite well. It should be noted, however, that none of those users operated BTM with a real-time task concurrent with time-sharing. In fact, XDS was unable to supply the name of any such users.

In summary, XDS appears to have a reliable hardware and software system; however, the support of their system has been somewhat less than completely satisfactory. Also, XDS real-time, time-sharing capabilities have been untested in the field.

D.2.6.3 Users' Comments on Digital Equipment Corporation PDP-10

The users contacted for the PDP-10 were hybrid users in all cases but one.

The users stated that the real-time as well as time-sharing capability of the software was excellent. One user had underestimated the multiple-user handling capability of the time-sharing software and consequently he is now increasing the number of time-sharing terminals in his system. Users have experienced a minimum of problems with the software. The basic software has been in existence since the mid 60's. It was originally written for the PDP-6. (The PDP-6 was the fore-runner to the PDP-10.) As a result both RT and time-sharing software for the PDP-10 has been used for a number of users and in various applications. The DEC FORTRAN IV was judged by one user to-be very general in that

it allowed variation in coding that other FORTRAN compilers would judge as errors. This could be a problem in running programs on the PDP-10 that had been run on other non-DEC computer systems; portions of the programs might have to be recoded.

... one complaint received was from a user who specified a non-standard piece of equipment that was to be built by DEC. DEC underestimated the development time and overestimated the capability of their field service people to install and troubleshoot this piece of equipment.

The overall capability and reliability of both hardware and software was deemed outstanding by the DEC PDP-10 users contacted. DEC personnel outstandingly supported both their hardware and software.

### D.2.6.4 Digital Computer Users' Comments - Summary

As a result of MIT's contacts with users of DEC, SEL and XDS computer systems, the following comments can be made.

- Digital Equipment Corporation users have been extremely satisfied with both the hardware and software supplied for the PDP-10 computer system, as well as the vendor support received on these items.

- Users of Systems Engineering Laboratories 8600 computer systems are in general satisfied. They understand that due to the newness of the system, hardware and software problems are to be experienced. These problems have not caused difficulties because of the excellent hardware and software support from SEL to their users.

- In general, users of Xerox Data Systems were satisfied with the hardware and software received. Many of the users were disappointed with the service and support they received from XDS pertaining to both their hardware and software.

### D.2.7 Benchmarks

One form of comparison of computer systems is that of a benchmark. A benchmark is a test wherein the salient characteristics of a test computer are observed while solving a series of test programs. For selecting a computer for a Navy Simulation Facility execution time is the characteristic that was tested. [*]

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[*] Other characteristics such as compilation time, load time, core requirements, accuracy of results, etc., could also be compared.

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It was decided to run a benchmark using programs that are typical of those to be solved in simulation on Air Cushion Vehicles. However, a set of such programs was not generated and an alternate approach was taken. Accordingly, four FORTRAN programs were obtained from a computer facility at MIT/Draper Laboratory. These programs were scientific in nature but not necessarily similar to those of ACV operations. They can, however, give an indication of the relative execution times for the computers under test.

It is suggested that if possible another benchmark be obtained with equations more similar to those that the computers will be required to solve in its intended application.

> Program 1 : Partial Differential Equation
>
> Program 2 : Bearing Analysis - uses many subroutines
>
> Program 3 : Matrix Multiplicatio.: - single precision
>
> Program 4 : Same as Program 3 except double precision

SEL, XDS and DEC were each asked to run the benchmark in a stand-alone configuration and in each case 100% satisfaction was not obtained.

SEL ran the benchmark at their facilities in Ft. Lauderdale, Florida. The SEL 8600 at this site is a prototype computer and consequently banks of core are constantly being shuttled in and out, and software is in a constant state of flux. (This is not an unusual condition for a prototype version of a computer.) One of the test programs required approximately 80K of core and the SEL computer only had 72K. Therefore, at best three of the four programs could be run. SEL ran programs 3 and 4 first but due to a malfunction at their site they were unable to run the other program.

XDS ran their benchmark on a Sigma 9 since a Sigma 8 was unavailable for the test. They stated that Sigma 8 and 9 execution times would be identical due to the similarities of the two computers. MIT/Draper Laboratories recommends repeating the test on a Sigma 8 at some later date. [*]

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[*] XDS was also asked to run the benchmark on a Sigma 5. Instead the benchmark was run on a Sigma 7 and MIT/Draper Laboratories was advised to add 15% to the execution times of the Sigma 7 to obtain Sigma 5 execution times. After reviewing the results obtained with previous results, a 30% addition seemed more in order.

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DEC had difficulty obtaining dedicated time on a PDP-10. Instead of
running the benchmark on a dedicated computer, they performed the
benchmark in a time-sharing model. It is reasonable to subtract 10%
for overhead incurred in time-sharing, however this was not done. DEC
estimates the PDP-10I to be between two and three times (closer to three)
faster than the PDP-10. A benchmark of the PDP-10I cannot be obtained
until September or October of 1971.

The SEL 8600 and XDS Sigma 5/7/8/9 have both single and double precision
floating point hardware. The PDP-10 has single precision floating point
hardware but double precision operations are done by software and con-
sequently such operations are considerably slower than if the hardware
were available. DEC advises that the PDP-10I will have double pre-
cision floating point hardware.

### RESULTS OF THE BENCHMARK
(Time in Secs)

|       | SEL 8600 dedicated | XDS 9 dedicated | PDP-10 time-sharing | IBM 360-65 |
|-------|--------------------|-----------------|---------------------|------------|
| Job 1 |                    | 803.8           | 1816.8              | 558.1      |
| Job 2 |                    | 344.0           | 546.8               | 180.8      |
| Job 3 | 199.2              | 169.2           | 517.8               | 195.9      |
| Job 4 | 296 9              | 255 5           | 1619.4              | 260.8      |

To add a reference, times were obtained for an IBM 360-65 (a much
more expensive computer than those considered here, but which the
reader may be more familiar with).

Indeed, the SEL 8600 and XDS Sigma 9 compared very favorably to the
IBM 360-65 Considering that the PDP-10I (if it performs as DEC claims)
will be approximately 2.5 faster in execution times than the PDP-10 and
that it will have double precision floating point hardware, as its compet-
itors did, it is reasonable to say all three of our test computers per-
formed quite well.

Modification of FORTRAN programs with in-line assembly language coding can often result in large savings in execution time. The DEC salesman claimed to have seen problem 3 previously and that he had reduced the PDP-10 execution time to approximately 120 seconds (from 317.8) by in-line coding. He claimed the enormous savings was obtained because the in-line coding was able to make up for an inefficiency in DEC's FORTRAN compiler.

The reader is cautioned again against drawing any firm conclusions from the benchmarks. One cannot subtract 10% time-sharing overhead and then divide the result by 2.5 to obtain PDP-10I times from PDP-10 time. One should not blindly convert Sigma 9 times to Sigma 8 times. One should not penalize SEL too harshly for not running the full set of benchmarks but by the same token the other one or two programs should be run. One must bear in mind that their FORTRAN compiler is the newest and may not be bug-free.

Overall, the exercise of running benchmarks on candidate computers was difficult. The quantitative data obtained can be used as a guide but requires caution in interpretation.

### D.2.8    Notes on Price Structure (Offerings)

The costs outlined in the RFI responses from the various digital computer vendors were taken from either their GSA or list price lists. Discounts or special offering may be available, however, since the vendors were responding to an RFI and not an RFQ it was felt to be inappropriate to negotiate at this time. Rental or leasing of the computers was not considered since such consideration merely would add another dimension to the investigation. It was felt that the prices as obtained were sufficient for this investigation.

Digital Equipment Corporation (DEC)

Digital Equipment Corporation (DEC) supplied list prices for all of their equipment suite applied in the RFI to Draper Laboratory.

DEC made mention in the RFI that when a configuration is finalized, current GSA prices would be quoted. Current GSA prices are seven percent below list prices for discountable items.

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## Systems Engineering Laboratories (SEL)

System Engineering Laboratories (SEL) supplied GSA prices for the equipment suite supplied to MIT in the RFI. Their 1070 GSA contract has provisions for discounts, which it is assumed will be retained in their 1971 GSA contract.

## Xerox Data Systems (XDS)

Xerox Data Systems (XDS) supplied an Authorized Federal Supply Schedule

## Price List in Their Response to the RFI

XDS usually allows a 10% discount in the purchase of their equipment by qualified non-profit educational and research institutions.

## Other Price Considerations

Each of the vendors has very little flexibility with regard to the purchase price and monthly maintenance cost for his equipment that is covered under GSA contract. However, there is considerable flexibility in other areas. Such items as

- Non-GSA standard products
- Non-standard hardware
- Special software
- Special training
- On-site maintenance
- System responsibility

can be included in an offering of significant savings. It is felt that of the three vendors, SEL would be most flexible in their offering.

### D.2.9 Facility Manning and Maintenance

The staff to support an open shop hybrid computer facility should consist of

- 1 computer supervisor

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- 2-3 engineer/programmers to assist users in analog and hybrid tasks.

- 2-3 engineer/programmers to maintain and assist in operations involving the monitor(s) and computer languages.

- 2 technical/operators to maintain analog equipment and assist in daily equipment operation.

Should users require their problems to be handled in total by the hybrid facility, the facility staff size would have to increase.

Any computer facility can be expected to have some down time — a good maintenance program will reduce that down time to a minimum. The obtained equipment should be serviced in accordance with the recommendations of the manufacturers.

Facility technicians should be responsible for the maintenance of the analog computer portion of the facility. They should be trained by the analog vendor and be capable of handling almost all the analog maintenance. An ample stock of equipment, as suggested by the analog vendor should be kept on hand.

Digital maintenance would be best performed, under a separate contract, by the digital vendor. Usually weekly maintenance will be required for the digital computer, mostly for peripheral devices. Since a service contract would include the weekly maintenance and replacement of all parts[*] as well as all other aspects of service to the digital components, it is felt that vendor maintenance would be more cost-effective than do-it-yourself maintenance. At a later date, if conditions so dictate, a self-maintenance program could be established, but for the first year or so the additional problems of self-service should not be added to the list of facility burdens.

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* This is a "part assurance contract" that would include all items.

# TYPICAL REQUEST FOR INFORMATION FORMAT

1. **Introduction**

    a. Basis for proposal

    b. Statement of the problem

    c. System approach (What, How, Why)

2. **Equipment Offering (Hardware)**

    a. Equipment suite (general description)

    b. Configuration diagram or diagrams

    c. Specifics regarding each item of the equipment suite or suites. (Basic cycle times, instruction list, instruction definition, instruction execution times, data transfer rates, core size, Gibson mix, minimum configuration required, etc.)

    d. Variations of the equipment suite to show flexibility of the system (growth potential)

    e. Equipment pricing of the equipment suite and variations to the equipment suite

3. **Equipment Offering (Software)**

    a. Operating system or systems (general description)

    b. Specifics regarding each operating system (core allocation, system timing, interrupt response time, other compilers, e.g., FORTRAN)

4. **Training**

    a. System operation training (hardware)

    b. System operation training (software)

5. **Field Software Support**

    a. Pre-installation support

    b. Installation support

    c. Post-installation support

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6. <u>System Reliability and Maintainability Factors</u>

7. <u>Installation and Acceptance</u>

(See the following Request for Information Agenda.)

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# REQUEST FOR INFORMATION

## AGENDA

1. **Equipment Specifications**

    a. **Main Frame**

    Basic cycle time, word size

    Instruction list

    Instruction definitions

    Instruction execution times

    Core size — Maximum, Minimum

    Benchmark

    Instruction — data registers (G.P. Register)

    Index registers

    Prior interrupts (normal - single inst.)

    Circ $T^2L$, DTL, MSI, etc.)

    Inter ng memory capability

    Multi-port memory

    Foreground Background capability

    Price lists

    Floating point format

    Macro programming

    Date first system delivered

    Customer list including contacts

    Additional register blocks (G.P.)

    b. **Peripherals**

    Minimum configuration for O.S.

    Data transfer rates

Line printer rates

Card reader rates

Card punch rates

Magnetic tape rates

Fixed head disc rates and storage

Moving head disc rates and storage

Price lists

c.   I/O Hardware

A/D capability

A/D input voltage specifications

A/D conversion rate  -  # of bits

Multiplexer capability

Multiplexer input voltage specifications

Multiplexer sampling rate

A/D-MVX accuracy  (single ended or differntial)

D/A capability

D/A dual rank storage

D/A conversion rate  -  # of bits

D/A accuracy

Signal line (discrete output) capability

Signal line voltage and current levels

Signal line $T^2$   DTL, MOS compatible

Test line       rete input) capability

Test line voltage levels

Test line $T^2$L, DTL, MOS compatible

Parallel data register (output) capability

Parallel data register (input) capability

Priority interrupt signal conditioning

Price lists

2. Software Specifications

Assemblers available

Compilers available

Operating systems available

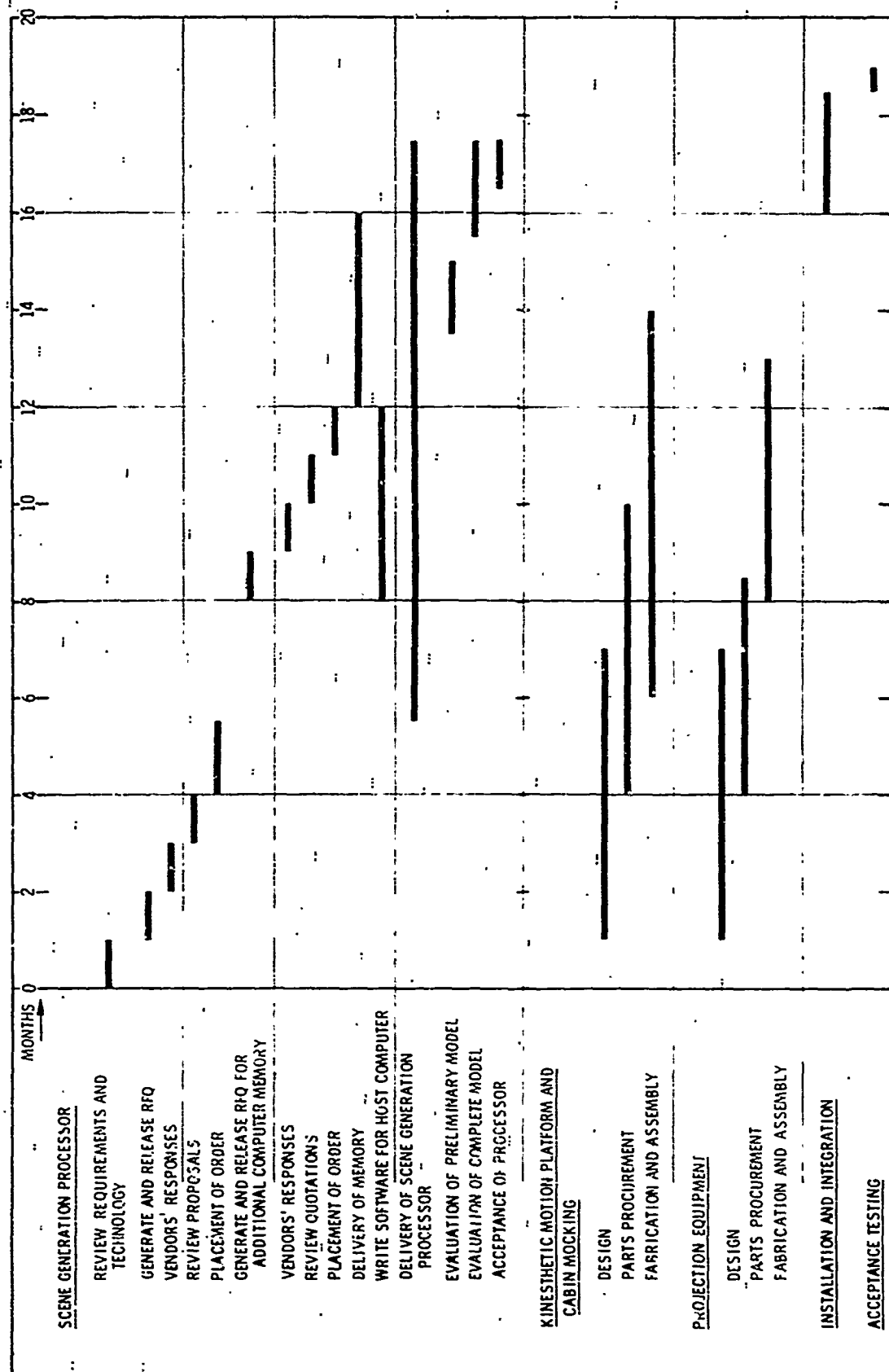Foreground-Background capability

O.S. core requirement

O.S. resident core requirements

Vendor software support

Customer list including contacts

O.S. response time to interrupts

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# VISUAL SIMULATION PROCUREMENT



MONTHS → (0, 2, 4, 6, 8, 10, 12, 14, 16, 18, 20)

**SCENE GENERATION PROCESSOR**

REVIEW REQUIREMENTS AND TECHNOLOGY

GENERATE AND RELEASE RFQ

VENDORS' RESPONSES

REVIEW PROPOSALS

PLACEMENT OF ORDER

GENERATE AND RELEASE RFQ FOR ADDITIONAL COMPUTER MEMORY

VENDORS' RESPONSES

REVIEW QUOTATIONS

PLACEMENT OF ORDER

DELIVERY OF MEMORY

WRITE SOFTWARE FOR HOST COMPUTER

DELIVERY OF SCENE GENERATION PROCESSOR

EVALUATION OF PRELIMINARY MODEL

EVALUATION OF COMPLETE MODEL

ACCEPTANCE OF PROCESSOR

**KINESTHETIC MOTION PLATFORM AND CABIN MOCKING**

DESIGN

PARTS PROCUREMENT

FABRICATION AND ASSEMBLY

**PROJECTION EQUIPMENT**

DESIGN

PARTS PROCUREMENT

FABRICATION AND ASSEMBLY

**INSTALLATION AND INTEGRATION**

**ACCEPTANCE TESTING**

MILESTONES AND AQUISITION PLAN FOR A NAVAL HYBRID SIMULATION FACILITY



REVIEW MIT REPORT AND NAVY
AGREEMENT ON CONSOLIDATION

WRITE RFQ

VENDOR RESPONSE TO RFQ

REVIEW RFQ RESPONSES

HIRE STAFF

WRITE USER SOFTWARE (FORTRAN)

PROCURE HYBRID INTERFACES
    ACCEPTANCE

PROCURE DIGITAL COMPUTER
    ACCEPTANCE

PROCURE ANALOG COMPUTER
    ACCEPTANCE

TRAINING
    ANALOG FAMILIARIZATION
    VENDOR DIGITAL TRAINING

FAMILIARIZATION WITH HYBRID FACILITY

EXERCISE MULTIACCESS CAPABILITY

CONDUCT OPEN SHOP SIMULATION

MILESTONES ▼

ANALYTICAL AND EXPERIMENTAL PLAN FOR
UPDATING ACV MATHEMATICAL MODEL

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